NASA Conference Publication 10041

Global Stratospheric Change

Requirements for a Very-High-Altitude Aircraft for Atmospheric Research

A Report of the Workshop
Truckee, California
July 15-16, 1989

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A Report of the Workshop
Sponsored by
NASA Ames Research Center
Truckee, California
July 15-16, 1989

NASA

National Aeronautics and
Space Administration

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PREFACE

The workshop on Requirements for a Very-High-Altitude Aircraft for Atmospheric Research, sponsored by NASA Ames Research Center, was held July 15-16, 1989, at Truckee, CA. The workshop had two purposes:

Assess the scientific justification for a new aircraft that will support stratospheric research beyond the altitudes accessible to the NASA ER-2, and to

Determine the aircraft characteristics (e.g., ceiling altitude, payload accommodations, range, flight duration, operational capabilities) required to perform the stratospheric research referred to in the justification.

To accomplish these purposes, the workshop brought together a cross-section of stratospheric scientists with several aircraft design and operations experts. The stratospheric scientists included theoreticians as well as experimenters with experience in remote and in situ measurements from satellites, rockets, balloons, aircraft, and the ground.

Discussions of required aircraft characteristics focused on the needs of stratospheric research. (A discussion of subsonic versus supersonic aircraft appears in Appendix A.) Nevertheless, it was recognized that an aircraft optimal for stratospheric science would also be useful for other applications, including remote measurements of Earth's surface (Appendix B). A brief description of these other applications was given at the workshop.

This report summarizes the discussions and conclusions of the workshop. Acronyms and references appear in Appendices C and D, respectively.

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EXECUTIVE SUMMARY

Background

The question of whether to develop an aircraft with ceiling and range in excess of those attainable by the ER-2 is raised by

marked success of the ER-2 in answering important questions about the stratospheric ozone balance that were unanswerable by other techniques,

remaining key scientific questions that can be addressed only with improved aircraft ceiling and range, and with payload capabilities similar to those of the ER-2, and

progress in aircraft technology since the development of the U-2 and ER-2, greatly improving the feasibility of attaining the altitudes, ranges, payload accommodations, and other characteristics needed to address the scientific questions.

The ER-2's recent successes derive from the aircraft's ability to carry a versatile payload to make highly controlled, high-resolution measurements in specific atmospheric regions of interest. This ability, denied to satellites and balloons, is enhanced by the high frequency of successful launches and recoveries of the ER-2.

Stratospheric science and, indeed, Earth science in general have always required a variety of experimental approaches, including satellite, balloon, aircraft, and ground-based studies. All indications are that this need for an integrated approach will continue indefinitely. The purpose of the workshop on Requirements for a Very-High-Altitude Aircraft for Atmospheric Research was to assess whether advances in very-high-altitude aircraft are required to complement the advances planned in other approaches, and if so, what advances are most critically needed and when.

Scientific Need for Improved Aircraft Capabilities

The workshop considered pressing scientific questions that require advanced aircraft capabilities and grouped those questions into proposed missions. It should be stressed that, in general, the science requires **both in situ and remote measurements** from the very-high-altitude aircraft, and that the vertical resolution of passive remote measurements benefits greatly from increased platform altitude. The missions are:

Mission 1: Polar Vortex Key questions include:

- **What causes ozone loss above the dehydration region in Antarctica?**
- **To what extent are dehydration, denitrification and ozone loss transmitted to midlatitudes?**
- **What are the abundances and the horizontal and vertical gradients of O_3, ClO, Cl_2O_2, BrO, NO, NO_2, OH, and HO_2 within the vortex?**
- **What maintains the geographical distribution of polar stratospheric clouds, and how do they transform the chemical balance as a function of temperature and pressure? How do polar stratospheric clouds and their underlying decks of high, cold cirrus affect the vertical motion field?**

This mission requires flights at a cruise altitude of 30 km (100,000 ft) from a South American base to the South Pole (a round trip of 5,000 to 6,000 n.mi.), a vertical profile from cruise altitude down to 14 km (45,000 ft) and back to cruise altitude, and the ability to fly into the polar night and over water more than 200 n.mi. from land. The range of atmospheric constituents and state variables to be measured implies a payload capability equal to or greater than that carried by the ER-2 in the AAOE and AASE missions (2,700 lb).

Mission 2: High-Altitude Photochemistry in Tropical and Middle Latitudes The key question is:

- **Do the abundances of O_3, O, OH, HO_2, NO, NO_2, Cl and ClO quantitatively account for the photochemical state of the middle and upper stratosphere, as a function of altitude, latitude, and measured solar flux?**

Traditionally high-altitude balloons have been used for atmospheric photochemical studies, but here the requirements go far beyond what can be accomplished with balloons. This mission requires the ability to cruise near an altitude of 30 km (100,000 ft) over wide latitude ranges (preferably from northern midlatitudes through the tropics to southern midlatitudes), or to stay aloft for a significant portion of the diurnal cycle. The ability to fly vertical profiles from cruise altitude down to about 10 km (33,000 ft), and to remain over water for long periods, is also required. The range of atmospheric constituents and state variables to be measured implies a payload capability equal to or greater than that carried by the ER-2 in the AAOE and AASE missions (2,700 lb). The ability to jump up to altitudes between 35 and 40 km (115,000-130,000 ft), even with a significantly reduced payload, is also highly desirable.

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Mission 3: Transport of Chemical Species by the General Circulation The key questions include:

- **Over the lifetime of the winter vortex, how much air is chemically processed and transmitted to midlatitudes?**

- **What is the chlorine content, and what are its chemical forms in the tropical middle stratosphere?**

- **How are the estimated lifetimes of chlorofluorocarbons affected by the diabatic cooling rates in and around the winter vortex?**

This mission requires the same capabilities as Mission 2.

Mission 4: Volcanic, Stratospheric Cloud/Aerosol, Greenhouse, and Radiation Balance. Key questions include:

- **How do volcanic injections, especially in their first few months, affect the chemistry of trace gases (including ozone) and radiation and temperature fields? How do particle physics and chemistry evolve during this period?**

- **How does the expected greenhouse cooling and moistening of the stratosphere affect the vertical and horizontal extent, and the particle microstructure, of stratospheric clouds and aerosols? How do these changes, in turn, affect ozone chemistry?**

- **What do stratospheric profiles of radiative fluxes and radiatively active constituents, in conjunction with tropospheric profiles, reveal about the onset and predicted evolution of the greenhouse effect?**

This mission requires the ability to cruise at altitudes of about 30 km (100,000 ft) over wide latitude ranges (5,000 n.mi.), to fly into the polar night, and to fly over oceans far from land. The ability to jump up to 35 or 40 km (115,000-130,000 ft) would be highly desirable. The need to fly an integrated suite of particle and gas samplers and sensors, plus sophisticated radiometers, implies a payload capability of several thousand pounds.

Correlative Measurements for Spacecraft and Ground-Based Profilers

Correlative measurements for space- and ground-based remote sensors include both **validation measurements**, which test the accuracy of the remote sensors, and **complementary measurements**, which supply information not obtainable by the remote sensors. Experience gained from past satellite campaigns points to a need for increased emphasis on correlative measurements for current and future remote sensing systems. In the past, balloons have provided the bulk of correlative measurements. However, their low frequency of successful launches, small number of available launch sites worldwide, inability to follow experimenter-chosen paths, and difficulty of payload recovery underscore the need for a better platform for this type of measurement.

A very-high-altitude aircraft could eliminate all these problems and could, moreover, obtain data along the viewing path of spaceborne limb scanners. Such an aircraft would need the ability to cruise at 30 km altitude (100,000 ft), jump up to 35 or 40 km (115,000 or 130,000 ft), and carry payloads similar to the ER-2s. The ability to fly in excess of several thousand n.mi. would greatly facilitate cross-calibration of the stations of the ground-based Network for the Detection of Stratospheric Change. The ability to fly in the polar night and over oceans without restrictions is highly desirable.

Current Status of High-Altitude Aircraft Technology

Recent studies of the status of aircraft technology conducted independently by NASA personnel and by personnel from the aeronautical industry under a NASA contract, resulted in essentially the same conclusion—that state-of-the-art knowledge in the critical engineering disciplines would provide the necessary technology for a scientific aircraft operating subsonically at 30 km (100,000 ft). However, to sustain a level cruise or even use a jump-up or zoom maneuver to attain 37 km (120,000 ft) (subsonically) is problematical and may not be achievable with current technology. Subsonic flight at 40 km (130,000 ft) will require major technological advances.

Required Aircraft Characteristics

The above scientific and correlative-measurement goals require the development of a higher-flying, longer-range complement to the ER-2, i.e., a multi-investigator, facility platform capable of accessing any spot on the globe in any season. Key specifications include a cruise altitude of 30 km (100,000 ft), subsonic cruising speed, a range of 6,000 n.mi. with vertical profiling capability down to 10 km (33,000 ft) and back at remote points, and a payload capacity of 3,000 lb. A capability to jump up to 35 or 40 km altitude (115,000-130,000 ft), even with a considerably reduced payload, is highly desirable. The required range, and the requirements to fly in the polar night and in an unrestricted manner over oceans, often from commercial airports and in sensitive airspaces, imply a need for both unmanned and manned operations.

The payload requirement is similar to that of the ER-2 (2,700 lb), in spite of the fact that weight reductions are possible in many current ER-2 instruments. The payload requirement accounts for the need for two-way telemetry, onboard data processing and command execution, instrument modifications to accommodate lower sampling pressures and densities, and measurement of more species and radiative fluxes as the sophistication of science increases. We recommend formation of a science user review committee to provide continuing oversight of both aircraft and instrument development.

The above multi-investigator, facility aircraft could address most but not all of the science questions described at the workshop and in this report. Building a more complex version of this aircraft to address the remaining questions would be too expensive. Specialized designs could, however, address the requirements of these upper atmospheric science questions.

Required Development Schedule: Aircraft and Instruments

Many of the science questions discussed in this report have enormous practical significance. They impact regulatory decisions that affect not only multibillion-dollar industries (chemicals, energy, aircraft) but also the bulk of the world's population through refrigeration, insulation, and other necessities of life. Minimizing regulatory conflicts between the developed and developing nations, as well as within the developed community, will require answers to the pertinent science questions on the shortest practical time scale, certainly on the order of five years.

The relationship of the proposed aircraft to other measurement systems also argues for very rapid development. The Upper Atmosphere Research Satellite (UARS) will be launched in 1991, and one of its most important instruments, the Cryogenic Limb Array Etalon Spectrometer (CLAES), will cease operation when it runs out of cryogen in mid-1993. This cessation and the subsequent deterioration of other UARS sensors will leave a critical gap in spaceborne measurements of the upper atmosphere before the first Earth Observing System (Eos) sensors come on-line in 1996 or later. If the proposed aircraft could begin operations while CLAES and the other UARS sensors are operational, it would make an important contribution to their validation, and it could extend measurements through the critical gap (roughly 1993-96) between the CLAES and Eos operational periods. Of course, the aircraft would also have ideal capabilities for validating and complementing many Eos sensors.

Similarly, the Network for the Detection of Stratospheric Change (NDSC), an array of ground-based upper atmosphere remote sensing instruments, will become operational near 1995. The very-high-altitude aircraft proposed here could perform an important role in cross calibrating NDSC stations and satellites via correlative measurements made above the stations in conjunction with satellite overpasses.

Thus, both the practical significance of the science questions and the relationship to other measurement systems (UARS, NDSC, Eos) argue for rapid development of the proposed aircraft, ideally by early 1993, and certainly by 1995.

In order to fully utilize the high-altitude aircraft it will be necessary to modify the ER-2 instruments or build new instruments for the lower operating pressures of the new aircraft. It is important that instruments be available as soon as the aircraft is ready so that observations can be initiated promptly. For these reasons we recommend that instrument development and modification be done in parallel with aircraft development.

Conclusions

The Workshop confirmed the importance of a diversity of sampling strategies and platforms to advance the science of the stratosphere. Satellites can provide global coverage, but are severely limited in spatial, and often temporal, resolution, as well as in the ability to respond quickly to new measurement requirements caused by new scientific questions. Balloons can provide vertical resolution for selected species but they are restricted both in time and space. There is an urgent need to provide access to altitudes higher than can be reached by the ER-2 and to enhance the available range.

The ideal platform would reach altitudes as high as 40 km (130,000 ft); it is here that perturbations to ozone due to anthropogenic chlorine are expected to be largest at mid-latitude. Effort should be directed to a search for imaginative sampling strategies capable of enhancing our sampling ability in situ in remote, inhospitable regions of the stratosphere. It is clear that answers to a number of the more important questions raised in this report will require diverse approaches.

We recommend development of an aircraft with the capacity to carry integrated payloads similar to the ER-2, but to significantly higher altitudes and preferably with greater range than is currently possible with the ER-2. It is important that the aircraft be able to operate over the ocean and in the polar night. This may dictate development of an autonomous or remotely piloted plane. There is a complementary need to explore strategies that would allow payloads of reduced weight to reach even higher altitude, enhancing the current capability of balloons.

WORKSHOP ATTENDEES

Name Organization	Expertise
James Anderson (P) Harvard U.	SS
Paul Bailey (P) NCAR	SS
Jim Barrilleaux (O) NASA Ames	AO
Steve Baughcum (O) Boeing Aerospace	AD
Edward Browell (P) NASA Langley	SS
William Brune (P) Penn State U.	SS
Alan Chambers (O) NASA Ames	GM
K. Roland Chan (O) NASA Ames	SS
Tom Clancy (O) Aurora Flight Sciences	AD
Estelle Condon (P) NASA Ames	SS
Paul Crutzen (P) Max Planck Institute	SS
David Fahey (P) NOAA Aeronomy Lab	SS
Crofton Farmer (Workshop Chair) JPL	SS
William Ferguson (O) Lockheed ADP	AO
Richard G. Johnson (O) USRA/Ames	ES
Harvey Kent (O) Lockheed	AD
George Kidwell (O) NASA Ames	AD
John Langford (O) Aurora Flight Sciences	AD
Howard Larson (O) NASA Ames	AS
Max Loewenstein (Report Co-editor) NASA Ames	SS
David Lux (O) NASA Ames/Dryden	AD
Lisa Mann (Workshop Coordinator) TGS Ames	ES
Michael McElroy (P) Harvard U.	SS
Hiro Miura (O) NASA Ames	AD
Lee Nicolai (O) Lockheed ADP	AD
Jack Nielsen (O) NASA Ames	AS
Rudolf Pueschel (P) NASA Ames	SS
Dale Reed (O) PRC Ames/Dryden	AD
Philip Russell (Workshop Organizer and Report Editor) NASA Ames	SS
Arthur Schmeltekopf (P) Retired	SS
Mark Schoeberl (P) NASA Goddard	SS
Brian Toon (P) NASA Ames	SS
Adrian Tuck (P) NOAA Aeronomy Lab	SS
Steven Wegener (O) NASA Ames	IM
John Wittenbury (O) NASA Ames	AO

Key:

- AD - Aircraft Design and Development
- AO - Aircraft Operations
- AS - Aeronautical Science
- ES - Earth Science
- IM - Instrument Management
- GM - General Management
- SS - Stratospheric Science
- P - Participant
- O - Observer

WORKSHOP ON REQUIREMENTS FOR A VERY-HIGH-ALTITUDE AIRCRAFT FOR ATMOSPHERIC RESEARCH

July 15-16, Truckee, CA

AGENDA

Saturday, July 15

PM		
5:00	DINNER, Schafer's Mill (Northstar Main Lodge)	
6:00	HQ View and Chairman's Charge	Farmer
6:10	Brief Sketch of Scientific Opportunities, Advantages, And Requirements for a Very-High-Altitude Aircraft	Russell
6:50	Examples of Unique Science From the ER-2 (What has the ER-2 Achieved that Satellites, Balloons, Rockets, and Ground Sensors Could Not?)	Tuck, Fahey, Pueschel
7:20	Critical Operational Factors	Barrilleaux
7:30	Aeronautical Possibilities & Constraints above 70,000 ft – Possible Aircraft Designs, Mission Profiles & Payload Accommodations – Mission Constraints Based on Aircraft Design Sensitivities	Kidwell
8:30	Harvard/MIT Ideas for Flight Above 70,000 ft	Anderson/Langford
8:45	What the Airplane Designers Need from This Meeting	Lux

Sunday, July 16

AM		
8:00	Expected Leading Questions in Stratospheric Science, 1992-2010 (e.g., SST Effects, CFC Effects, Heterogeneous Chemistry, Solar Cycle, Greenhouse Cooling, Humidification, Diurnal Cycles, Polar Stratospheric Clouds, Volcanoes, ...)	McElroy, Toon, Tuck, (Russell for Crutzen)
9:00	Expected Scientific Role and Gaps of UARS, Eos, Other Satellites, & Ground Network, 1991-2010	Tuck, Schoeberl

Sunday, July 16 (Cont'd)

9:30	Report of Subsonic vs. Supersonic Committee	Schmeltekopf
9:45	Probable Very-High-Altitude Aircraft Costs Relative to Other Techniques	Lux, Schoberl, ...
9:55	BREAK	

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10:10	Brainstorming: How Would a Very-High-Altitude Aircraft be Used to Fill the Gaps? (Groups A-D. Chairs & Topics as Shown Below)	
11:45	Viewgraph Writing	Groups A-D
12:00	LUNCH	
PM		
12:30	Group Reports: Unique Atmospheric Science a Very-High-Altitude Aircraft Could Do	
	A. In Situ Gas Chemistry (incl diurnal cycle)	Anderson
	B. Particle Chemistry & Physics	Toon
	C. Remote Chemistry	Browell
	D. Dynamics	Tuck
1:30	Very-High-Altitude Aircraft Role in Validation & Complementary Measurements for Space- & Ground-based Remote Profilers	Russell, Bailey
1:40:	Very-High-Altitude Aircraft Application to Remote Sensing of Earth's Surface	Johnson
1:50	Writing Assignments: Questions 1, 2, & 3 (incl ↵)	Farmer
1:55	Discussion, Viewgraph Writing	Groups 1-3 (See Below)
3:30	BREAK	
3:45	Summary Reports	
	–Grp/Question 2 (What Science & Advantages?)	Tuck
	–Grp/Question 3 (Requirements, incl Schedule)	Schmeltekopf
	–Grp/Question 1 (Is a Very-High-Altitude Aircraft Justified?)	McElroy
4:50	Review of Writing, Assembly, & Review Schedule	Farmer
5:00	Adjourn	

1. INTRODUCTION

Studies of the chemistry and dynamics of the stratosphere require a variety of approaches. The subject has advanced remarkably over the past 20 years, stimulated in large measure by concerns that the activities of humanity can result in significant changes in the abundance of stratospheric ozone (O_3). Observations from satellites, rockets, balloons, aircraft, and the ground have all played a role. This document is concerned largely with facilities for local, as opposed to global, measurements, whether by remote sensing or in situ sampling. We shall review briefly current capabilities of aircraft and balloons. Then, in the context of present understanding of stratospheric chemistry and dynamics, we shall identify specific areas of atmospheric study in which existing sampling capabilities are inadequate.

Balloons played a particularly important part in the early in situ exploration of the stratosphere. They provided profiles for species such as H_2O, CH_4, N_2O, and a number of the industrial chlorocarbons, whose decomposition represents the dominant source of the hydrogen, nitrogen, and chlorine radicals now known to control the abundance of ozone. Balloons yielded the first direct measurements of the reactive species NO, NO_2, O, Cl, and ClO, in addition to O_3. Interpretation of the balloon results was hampered, however, by the relatively sparse data set obtained. Restrictions on payload weight, even for the largest balloons, limited measurements on any given flight to a small number of atmospheric constituents, over an altitude range of about 10 to 40 km (33,000 to 130,000 ft). Measurements could be taken at only a limited number of locations, and temporal coverage was exceedingly sparse. Moreover, experimenters had little flexibility in directing payloads to study specific phenomena; balloons were constrained to follow the wind, and interesting regions were often inaccessible.

Aircraft have played a dominant role in the recent history of stratospheric science. In situ and remote measurements from the ER-2 and the DC-8 on the Airborne Antarctic Ozone Experiment (AAOE) mission in 1987 provided a wealth of essential information on the phenomenon of the Antarctic ozone hole. Large losses in the column abundance of ozone in spring over Antarctica had been documented from ground-based measurements made by the British Antarctic Survey at Halley Bay (Farman et al., 1985). The record from Halley Bay, dating back to 1957, indicated that the ozone loss began in the mid-1970s and accelerated markedly in the 1980s. The data from Halley Bay were confirmed and placed in a larger geographic context on the basis of careful analyses of measurements from the Total Ozone Mapping Spectrometer (TOMS) on the Nimbus-7 satellite. These measurements stimulated a number of hypotheses to account for the surprising loss of ozone. Explanations were proposed postulating the production of chlorine radicals by reactions occurring on the surfaces of polar stratospheric clouds (Solomon et al., 1986; McElroy et al., 1986). Specific mechanisms were advanced, one suggesting a catalytic scheme involving HOCl (Solomon et al., 1986), a second invoking the reaction of ClO with BrO (McElroy et al., 1986), a third postulating a catalytic scheme involving photolysis of the ClO dimer (Molina and Molina, 1987). A second class of explanation, suggested by Callis and Natarajan (1986), argued that the ozone hole could be a natural phenomenon, attributable to catalytic loss of ozone caused by large concentrations of NO_x formed during periods of high solar activity. Tung et al. (1986) offered a dynamical explanation, invoking rapid upward motion of the lower stratosphere.

Ground-based data obtained during the National Ozone Expedition (NOZE 1) to McMurdo Station, Antarctica, in 1986 confirmed the presence of high concentrations of ClO in the springtime Antarctic stratosphere and provided the first indirect evidence for large abundances of BrO (Solomon et al., 1987). Abundances of NO_x were low, allowing the hypothesis of Callis and Natarajan (1986) to be rejected. It was left, however, to the AAOE to provide definitive proof that the loss of ozone over Antarctica was due largely to industrial chemicals. Measurements of N_2O made by the ER-2 (Podolske et al., 1989; Loewenstein et al., 1989; Heidt et al., 1989; Hartman et al., 1989) showed that vertical motion inside the South Polar vortex was directed down, rather than up. Measurements of ClO by Anderson et al. (1989) and O_3 by Proffit et al. (1989) and Starr and Vedder (1989) showed that concentrations of these species were inversely correlated inside the vortex. The ER-2 data demonstrated that the bulk of the springtime loss of ozone over Antarctica can be attributed to a combination of the mechanisms suggested by Molina and Molina (1987) and McElroy et al. (1986).

The Antarctic phenomenon was ideally suited to the capabilities of the ER-2, with several important caveats. The aircraft was able to carry a large complement of relevant instruments to an altitude located in the heart of the disturbed region, but its range was too short to penetrate the vortex as deeply as the experimenters wished. This limitation is reduced to some extent when data from the ER-2 are combined with more extensive remote sensing measurements from the DC-8. The ER-2's range restrictions pose serious problems, however, for subsequent missions to Antarctica designed to study the chemical conditioning of the stratosphere that is expected to take place during local winter. Operational requirements for the aircraft dictate that it be based further north at this season, making it unlikely that the ER-2 could penetrate to the region of interest. The

fact that the ER-2 is a piloted, single-engine aircraft implies two additional restrictions. Namely, it cannot fly into the polar night, and it cannot make unrestricted flights over water more than 200 n.mi. from land. These restrictions have become increasingly important, not only for studying wintertime chemical conditioning, but also for accessing stratospheric clouds in their most favorable locations, which are often far from land.

The Airborne Arctic Stratospheric Expedition (AASE), carried out early in 1989 to study the behavior of ozone in the Arctic, offered further testimony to the powerful capability of a carefully selected payload of airborne instruments in studying phenomena as complex as the behavior of stratospheric ozone. The altitude region of primary interest was located, to a larger extent than for Antarctica, above the ceiling of the ER-2. Detailed follow-on studies of ozone loss over the Arctic will require aircraft capable of carrying the payload capacity of the ER-2 to altitudes as high as 30 km (100,000 ft), with a significant range at altitudes of about 20 km (65,000 ft), as elaborated below. The ability to reach higher altitude is also essential for study of the midlatitude and tropical stratosphere; with the exception of the southern polar region, the bulk of stratospheric ozone lies above the altitudes accessible to the ER-2.

The Workshop confirmed the importance of a diversity of sampling strategies and platforms to advance the science of the stratosphere. Satellites can provide global coverage, but are severely limited in spatial, and often temporal, resolution. Balloons can provide vertical resolution for selected species but they are restricted in both time and space. There is an urgent need to provide access to altitudes higher than can be reached by the ER-2 and to enhance the available range.

The ideal platform would be able to reach altitudes as high as 40 km (130,000 ft); it is here that perturbations of ozone caused by anthropogenic chlorine are expected to be largest at midlatitude. Effort should be directed to a search for imaginative strategies to enhance our in situ sampling ability in remote, inhospitable, regions of the stratosphere. A diversity of approaches will be required to answer the more important questions raised below.

We recommend development of an aircraft with the capacity to carry integrated payloads similar to the ER-2 to significantly higher altitude, preferably with greater range. It is important that the aircraft be able to operate over the ocean and in the polar night. This may dictate development of an autonomous or remotely piloted plane. There is a complementary need to explore strategies that would allow payloads of reduced weight to reach even higher altitude, enhancing the current capability of balloons; ways to meet this need were addressed at the workshop. These approaches showed promise, and we urge that they be explored further. To the extent that flexible, high-altitude platforms could be developed and used to provide access to the stratosphere at relatively low cost, they could play an invaluable and essential role in testing new instrument concepts and in training the next generation of stratospheric scientists. In this context we note with concern the relative absence of the academic community from the recent aircraft campaigns. For the health of the subject, this situation must be corrected.

2. CRITICAL SCIENCE QUESTIONS UNIQUELY ADDRESSABLE BY VERY-HIGH-ALTITUDE AIRCRAFT

The stratosphere has three broad geographical divisions: polar, midlatitude, and tropical, each with its own crucial, unanswered questions with regard to the ozone balance. How the general circulation affects the communication of chemical transformations between them is a further question. Recent missions using high-altitude aircraft have proven that the aircraft can answer key questions regarding the ozone balance, demonstrating, for example, that the Antarctic ozone hole is largely caused by chlorine released by stratospheric photo-oxidation of chlorofluorocarbon (CFC) molecules. This power stems from the aircraft's ability to carry a versatile, wide-ranging payload making high-resolution measurements into specific atmospheric and geographic regions of interest in a highly controlled manner. This ability, denied to satellites and balloons, is enhanced by the high frequency of successful launches and recoveries. It also permits rapid scientific analysis of the data, often within hours, thus allowing subsequent flights to incorporate the lessons learned; that is, the basic scientific experimental procedure of trial and response is flexibly incorporated.

The very success of the recent missions of the ER-2 has laid bare some further critical questions which cannot be answered without significant enhancement of the operational envelope, particularly in altitude and range. Such operational requirements are detailed in chapter 5. While any adequately instrumented aircraft is inherently capable of addressing a wide range of questions in atmospheric chemistry, the workshop selected four critical missions for study. These missions are urgent; they must be addressed within 5 years. It should be stressed that, in general, this research requires **both in situ and remote measurements** from the very-high-altitude aircraft, and the vertical resolution of passive remote measurements benefits greatly from increased platform altitude.

Mission 1: Polar Vortex

Science Questions– The science questions addressed by this mission are those remaining from, or raised by, the AAOE, August-September 1987, and the AASE, January-February 1989. These include:

What causes ozone loss above the dehydration region in Antarctica?

Papers in the AAOE special issue of the *Journal of Geophysical Research* (vol. 94, 1989) argue that the signature of ozone loss over Antarctica in 1987 extended to at least 30 km (100,000 ft), well above the ER-2 ceiling and well above the region where dehydration can occur. We do not know how such ozone loss occurs, and hence we are unable to predict the extent of its spatial or temporal propagation as the inorganic chlorine abundance increases.

To what extent are dehydration, denitrification, and ozone loss transmitted to midlatitudes?

The AAOE special issue also contains papers which argue that the Antarctic vortex is not completely isolated and that the effects of chemical transformations within it may be transmitted to midlatitudes. Such mechanisms would propagate ozone loss to midlatitudes; until we understand them quantitatively, we cannot predict their behavior as the amount of inorganic chlorine rises.

What are the abundances and the horizontal and vertical gradients of O_3, ClO, Cl_2O_2, BrO, NO, NO_2, OH, and HO_2 within the vortex?

Prediction of future ozone loss within the vortex depends on quantitative characterization of the chemical loss mechanisms. Until measurements of all the chain-carrying species are available in the core of the vortex, approximately poleward of 70° S., this ability will not be in hand.

What maintains the geographical distribution of polar stratospheric clouds, and how do they transform the chemical balance as a function of temperature and pressure? How do polar stratospheric clouds and their underlying decks of high, cold cirrus affect the vertical motion field?

The detailed mechanism of denitrification, and its relationship to dehydration, are not completely understood. These processes set up the chemical imbalance that allows the halogen free radicals to destroy ozone; since they are forced by tropospheric weather systems, the year-to-year variability and the long-term trend in ozone loss are sensitive to climate fluctuations as well as to future halogen abundances. Geographically, polar stratospheric clouds in Antarctica are statistically most frequent in the longitude sector between 90° W. and 10° E., over the Weddell Sea, at altitudes up to 30 km (100,000 ft). This is a region available to the necessary in situ instruments only by a long-range, very-high-altitude aircraft. Polar stratospheric clouds may also affect the radiative balance and hence the extent of downward motion in the vortex.

Required Altitudes, Ranges, Locations, and Other Considerations– This mission requires flights at 30 km (100,000 ft) cruise altitude from a South American base to

the South Pole (a round trip of 6,000 n.mi.), with a vertical profile from cruise altitude down to 14 km (46,000 ft) and back to cruise altitude, and the ability to fly into the polar night and over water more than 200 n.mi. from land. The range of atmospheric constituents and state variables to be measured implies a payload capability equal to or greater than that carried in the AAOE and AASE missions (2,700 lb).

Mission 2: High-Altitude Photochemistry in Tropical and Middle Latitudes

Science Question– This mission aims to answer the following question:

Do the abundances of O_3, O, OH, HO_2, NO, NO_2, Cl, and ClO quantitatively account for the photochemical state of the middle and upper stratosphere, as a function of altitude, latitude, and measured solar flux?

In order to test the homogeneous, gas-phase photochemistry in the stratosphere, it is necessary to measure simultaneously the atoms, free radicals, and molecules which carry the ozone-destroying chain reactions. The time constants for these reactions become progressively shorter at higher altitudes, and the response to the diurnal variation of sunlight becomes more detectable. It is very difficult for satellites to sample the local diurnal variation adequately, and balloons have had only limited success in a very restricted spatial and temporal regime. There is thus a clear need for a very-high-altitude, long-endurance aircraft to tackle this mission both in the tropics and in midlatitudes.

Required Altitudes, Ranges, Locations, and Other Considerations– This mission requires the ability to cruise near 30 km altitude (100,000 ft) over wide latitude ranges (preferably from northern midlatitudes through the tropics to southern midlatitudes), or to stay aloft for a significant portion of the diurnal cycle. The ability to fly vertical profiles from cruise altitude down to about 10 km (33,000 ft), and to remain over water for long periods, is also required. The range of atmospheric constituents and state variables to be measured implies a payload capability equal to or greater than that carried in the AAOE and AASE missions (2,700 lb). The ability to jump up to altitudes between 35 and 40 km (115,000-130,000 ft), even with a significantly reduced payload, is highly desirable.

Mission 3: Transport of Chemical Species by the General Circulation

Science Questions– This mission aims to answer the following questions:

Over the lifetime of the winter vortex, how much air is chemically processed and transmitted to midlatitudes?

What is the chlorine content, and what is its speciation, in the tropical middle stratosphere?

How are the estimated lifetimes of CFCs affected by the diabatic cooling rates in and around the winter vortex?

These are aspects of broader problems connected to the efficiency with which fluid mechanical motions in the stratosphere transmit the results of chemical transformations from one region to another. One of these problems is whether the winter vortex is a processor in the sense of being a chemical flow reactor. The second problem, which is in part tied to the winter vortex, concerns the speed of the circulation of CFCs from the tropics and midlatitudes, where they are photodissociated and release reactive chlorine in the middle and upper atmosphere, to the high latitudes where the air sinks as a result of radiative cooling, particularly in winter. The lifetime of reactive chlorine in the stratosphere, and hence its ozone-destroying potential, depends on the speed with which the general circulation moves this chlorine through the primary ozone-destroying regions. One such region is the middle and upper stratosphere in the tropics and midlatitudes, where ozone destruction is dominated by homogeneous gas-phase photochemistry. The other is the winter polar vortices, where heterogeneously perturbed chemistry prevails.

Both fluid mechanical modeling and some limited measurements suggest that conceptually there are restraints on the exchange of air across the subtropics and across the polar-night jet. It is thus crucial to understand the transfer processes connecting the tropics, the midlatitudes, and the polar regions. An instrumented aircraft on long meridional flights making simultaneous high-resolution measurements of reactive chemicals and tracers has the unique ability to reveal the signatures of such transfer. Local flights can address the question of which meteorological systems cause episodes of transport between the regions. Of particular importance are high-resolution measurements in the high-wind-shear region between the subtropics and the polar jet. A further key requirement is the measurement of the radiative flux divergence, particularly at high latitudes, to determine cooling rates and hence the downward velocity of air inside the vortex.

Required Altitudes, Ranges, Locations, and Other Considerations– This mission requires the same capabilities as Mission 2.

Mission 4: Volcanic, Stratospheric Cloud/Aerosol, Greenhouse, and Radiation Balance Studies

Science Questions– This mission primarily addresses questions about the impact of volcanic injections on the stratosphere and about the Earth's radiation balance (including the greenhouse effect). In addition, it addresses questions relating to stratospheric clouds and aerosols in general. Although polar stratospheric clouds are a subject of missions previously described, they are also included in this mission because of their radiative importance and the impact the greenhouse effect is expected to have on them.

Key questions addressed by this mission include:

How do volcanic injections, especially in their first few months, affect the chemistry of trace gases (including ozone), as well as radiation and temperature fields? How do particle physics and chemistry evolve during this period?

Previous studies have shown that the intermittent injections of particles and gases into the stratosphere by explosive volcanic eruptions often occur at altitudes above the ER-2 ceiling of 21 km (70,000 ft). These studies have found marked effects on the stratospheric radiation balance and temperatures, and some studies have suggested effects on the ozone layer. The ozone effects are unconfirmed, however, because of an inability to reach the volcanic injections during their initial evolution, and because the volcanic injections interfere with remote measurements of stratospheric ozone, interacting gases, and temperature. Thus there is a critical need for a platform to carry, on short notice, ER-2-type instruments that measure particles, radiation, and interacting gases to the altitudes and locations of fresh volcanic plumes—which are often well above the ER-2 ceiling and are rapidly carried over oceans by the zonal circulation.

How does the expected greenhouse cooling and moistening of the stratosphere affect the vertical and horizontal extent, and the particle microstructure, of stratospheric clouds and aerosols? How do these changes, in turn, affect ozone chemistry?

The subject of volcanic stratospheric aerosols relates to the unique abilities of high-altitude aircraft to measure stratospheric aerosols and clouds in general. Recent missions have shown that aircraft are unsurpassed in their ability to reach clouds and measure the properties of their individual particles (e.g., size, chemical composition, phase, shape) in conjunction with interacting trace gases and radiation fields. However, many of the most important stratospheric clouds occur above the ER-2 ceiling, in the polar night, or over water areas inaccessible to the ER-2.

This inaccessibility is expected to increase because the inexorable accumulation of greenhouse gases (e.g., CFCs, CO_2, CH_4, N_2O) in the Earth's atmosphere is expected to lead not only to tropospheric warming and moistening, but also to stratospheric cooling and moistening. Either the cooling or the moistening is expected to cause stratospheric clouds (both of ice and of condensed nitric, sulfuric, and hydrochloric acids) to appear more frequently over wider areas. Such clouds play a critical role in ozone depletion and also in the stratospheric radiation balance, which in turn affects stratospheric vertical motions and hence the formation of polar vortices. The importance of stratospheric cloud studies already points to a critical need to exceed the altitude, range, and operational envelope of the ER-2. The expected greenhouse cooling and moistening of the stratosphere greatly increases this need.

What do stratospheric profiles of radiative fluxes and radiatively active constituents, in conjunction with tropospheric profiles, reveal about the onset and predicted evolution of the greenhouse effect?

Studies of the greenhouse effect, especially those to detect its onset and predict its course, require highly accurate, repeatable measurements of radiative fluxes from the Earth's surface to altitudes above the important radiatively active gases (hence above the bulk of stratospheric ozone, carbon dioxide, and water vapor). This implies a need for repeated aircraft flights to altitudes of 30 km (100,000 ft) and above with a very good spectral radiometer, covering a latitude range greatly exceeding that typically flown by the ER-2.

Required Altitudes, Ranges, Locations, and Other Considerations– This mission requires the ability to cruise at altitudes of about 30 km (100,000 ft) over wide latitude ranges (5,000 n.mi.), to fly into the polar night, and to fly over the oceans far from land. The ability to jump up to 35 or 40 km (115,000-130,000 ft) is highly desirable. The need to fly an integrated suite of particle and gas samplers and sensors, plus sophisticated radiometers, implies a payload capability of several thousand pounds.

Conclusions

There is a pressing set of questions related to stratospheric ozone and the Earth's radiation balance which need to be answered within the next five years. Four missions have been proposed to answer those questions; they require the unique capabilities of a very-high-altitude, long-range aircraft. Without answers to these questions, prediction of

the effects of chlorine and bromine on the ozone balance will depend on inadequately tested models, which failed to predict the recent dramatic loss of ozone over Antarctica and the movement of air depicted in CFCs down rapidly enough at high latitudes in winter. Further questions regarding the Earth's radiation balance, which have enormous practical significance, will also remain.

3. CORRELATIVE MEASUREMENTS FOR SATELLITES AND GROUND-BASED PROFILERS: THE NEED FOR ENHANCED AIRCRAFT CAPABILITIES

Correlative Measurement Needs and History

When used in the context of remote measurements from satellites and the ground, the term "correlative measurements" has come to include two general components:

validation measurements, which attempt to measure the same parameter as the satellite or ground remote sensor to demonstrate the validity of the remote measurements, and

complementary measurements, which determine properties not measurable by the satellite or ground remote sensor, but which need to be known as part of the science investigation addressed by the remote sensors.

Correlative measurement efforts have been a significant component of all major atmospheric satellite programs (e.g., Nimbus-7, SAM/SAGE). However, it is clear that many previous efforts have been inadequate, and that increased emphasis on correlative measurements (both validation and complementary) will be needed in the future.

For example, careful investigations by the Ozone Trends Panel (Watson et al., 1988) revealed that the initially archived data from the Nimbus-7 Solar Backscatter Ultraviolet (SBUV) and TOMS instruments were in error, having been based on unjustified and incorrect assumptions about the degradation of the diffuser plate common to both instruments. Those data had been used to infer large global decreases since 1979 in the total column of ozone (about 1% per year) and in the ozone concentration near 50 km (165,000 ft) altitude. Both the data and the inferences had to be retracted as a result of the Ozone Trends Panel investigations. (The SBUV and TOMS data, now reanalyzed by normalization to coincident measurements by ground-based Dobson spectrometers, reveal much smaller but still significant ozone decreases.)

Partly as a result of the SBUV/TOMS experience, future spaceborne measurement programs (e.g., the Upper Atmosphere Research Satellite (UARS) and the Earth Observing System (Eos)) call for increased emphasis on correlative measurements. Similarly increased emphasis will be needed for the ground-based remote sensors in the Network for Detection of Stratospheric Change (NDSC). The major goal of NDSC is to provide the earliest possible detection of changes in the stratosphere and the means to understand them. Subsidiary goals are to study temporal and spatial variability of atmospheric composition and structure, and to provide the basis of validation and complementary measurements for UARS. All these goals require an unprecedented degree of quality control through rigorous calibration procedures and comparisons. The desired quality control is particularly ambitious considering the wide range of parameters that NDSC desires to measure. These include not only column ozone, the ozone vertical profile from 0 to 70 km (0-230,000 ft), and temperature from 0 to 70 km (0-230,000 ft), but also vertical profiles of ClO, H_2O, aerosols, NO_2, CH_4, N_2O, column HCl, and possibly HNO_3, OH, and $ClONO_2$.

Previous satellite correlative measurement programs have relied very heavily on balloon measurements. The reason is clear: only balloons could span the required altitude range (roughly from the tropopause up to 40 km (130,000 ft) or higher) with the necessary instruments. However, the inherent difficulties with large-payload balloons (few launch sites worldwide, launch opportunities highly restricted by local weather and stratospheric winds, lack of trajectory control, significant risk of payload loss) greatly restricted the number of successful coincidences between satellite and correlative measurements. The coincidences that were achieved rarely provided the necessary coverage of seasons, latitudes, hemispheres, and altitudes to conclusively investigate possible errors in the raw satellite data and in processing algorithms. This was certainly true for many ozone sensors, and even more so for the more difficult measurements (e.g., H_2O, NO_2, HNO_3).

The Potential Role for Very-High-Altitude Aircraft

An aircraft capable of carrying integrated payloads to heights of 30 or 40 km (100,000-130,000 ft) could solve many of the correlative measurement problems. The most immediate improvements would be the tremendous increase in launch sites worldwide and the ability to launch with greater frequency, independently of stratospheric winds and less restricted by surface weather. These advantages alone would greatly increase the ability to obtain, for a wide range of atmospheric constituents and state variables, coincidence between correlative and remote profiles in the requisite set of seasons, latitudes, hemispheres, and other conditions (e.g., phase of quasi-biennial oscillation, volcanic versus background aerosol conditions, phase of solar cycle).

Additional advantages stem from the aircraft's ability to follow an experimenter-chosen path. This includes the ability not only to fly at the location and time of the remote profile (to a much greater extent than balloons), but also to **fly along the exact limb path viewed by satellite limb scanners**. This ability was demonstrated by the U-2 in the SAGE II validation campaign (Oberbeck et al., 1989), and it proved

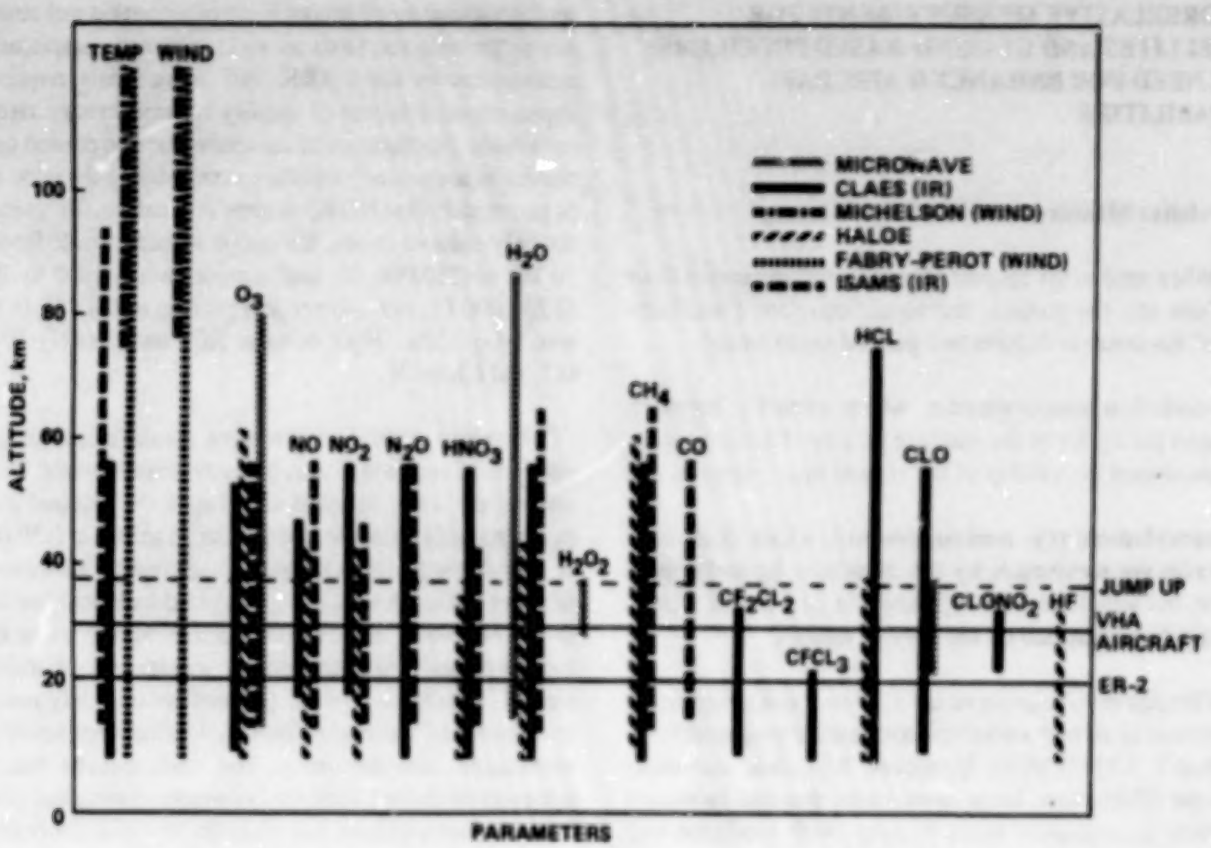

Figure 3.1.– Expected height range of measurements by the Upper Atmosphere Research Satellite compared with the height of ER-2 cruise and very-high-altitude aircraft cruise and jump up maneuvers.

very useful in documenting inhomogeneities along the viewing path and in identifying situations in which the desired homogeneity occurred.

Because of their limited ceiling of 21 km (70,000 ft), the U-2 and ER-2 have not been used extensively in other satellite and ground-based profiler validations. However, extending the aircraft ceiling to 30 or 40 km (100,000-130,000 ft) would remove the aircraft's major shortcoming and afford all the advantages of greater spatial and temporal access and control. Figure 3.1 compares the hoped-for height ranges of the various UARS measurements with the ceilings of the ER-2 and proposed aircraft. The ER-2 ceiling is near the lower edge of many of the most interesting measurements and below the region of many polar stratospheric clouds, whose effects on the UARS measurements need to be carefully investigated. The proposed 30- and 37-km (100,000- and 120,000-ft) ceilings, on the other hand, are close to the heart of many of the satellite profiles and span the region of polar stratospheric cloud interference.

The subject of polar stratospheric clouds, and aerosol and cloud particles in general, returns us to the second component of correlative measurements, namely the **complementary measurements**, which cannot be made by the satellite but which are needed to do the science addressed by the satellite. It is significant that UARS does not include any aerosol/cloud measurements. This is so in spite of the potential for aerosol/cloud interference in UARS measurements, not to mention the scientific importance of the aerosol/cloud particles in stratospheric chemistry and radiation. (Both the interference and the scientific importance are expected to increase over the next decades as greenhouse cooling and moistening of the stratosphere occur.) The recent AAOE and AASE campaigns have demonstrated the unequalled excellence of high-altitude aircraft in reaching stratospheric clouds and aerosols and in determining their individual-particle properties (size, chemical composition, phase, and shape). This capability would provide a much-needed complement to the trace gas measurements of UARS and other satellites, including Eos. (The SAGE III aerosol measurements planned for Eos use the solar occultation technique and thus will not coincide spatially and temporally with many of the Eos trace gas measurements. Moreover, it is highly doubtful that spaceborne techniques will ever measure the chemical composition of individual aerosol and cloud particles to the extent that aircraft can.)

The advantages of a very-high-altitude aircraft for satellite correlative measurements apply as well to ground-based remote sensor correlative measurements. With sufficient range, altitude, and payload capability, a single, integrated aircraft payload could measure vertical profiles in coincidence with one station of the NDSC, then rapidly fly to another station and fly vertical profiles there. In this way the relative calibration of the stations could be checked for a wide variety of atmospheric constituents. Repeated laboratory calibrations of the in situ instruments could also be used to monitor the long-term stability of the NDSC calibrations. Thus the very-high-altitude aircraft could uniquely supply one of the most critical needs of NDSC: a very accurate interstation calibration and a means of checking long-term stability.

4. CURRENT STATUS OF HIGH-ALTITUDE AIRCRAFT TECHNOLOGY

Designing an airplane to fly subsonically at altitudes of 30 km (100,000 ft) or more presents a unique and challenging problem to the aeronautical engineering profession. The problem starts with the extremely low atmospheric density at these altitudes. The amount of lift that a given airplane wing size can produce is proportional to the atmospheric density. The atmospheric densities at 21 km (70,000 ft) and 30 km (100,000 ft) are approximately 1/20 and 1/70, respectively, of that at sea level. Therefore, at a given velocity, a given airplane wing can produce only 1/20 the lift at 21 km (70,000 ft) and only 1/70 the lift at 30 km (100,000 ft) than at sea level. Altitudes higher than 30 km (100,000 ft) compound the problem further; for example, the atmospheric density at 37 km (120,000 ft) is only 1/180 that at sea level. However, tradeoffs can be made to bring the lifting forces into equilibrium in order to sustain cruising flight at altitudes as high as 30 km (100,000 ft).

Wing lift is proportional to atmospheric density, wing area, wing lift efficiency factor (C_L), and velocity squared. The design problem, then, can be solved by three basic means: increase wing area, decrease aircraft weight, or increase wing lift coefficient C_L.

The velocity is limited by the maximum subsonic Mach number that can be achieved without Mach buffet. This speed is near a Mach number of 0.7. The proper selection of wing airfoil section can maximize this speed and increase C_L.

System-Level Alternatives

An increase in wing area has practical operational limits, so structural weight must also be minimized and aerodynamic efficiency maximized. Table 4.1 lists several aircraft configuration options that are candidates for design tradeoffs. For example, the unusual joined wing concept shown in figure 4.1a may have lighter structure because of vertical bracing, but its aerodynamic efficiency is in question because of increased drag caused by mutual interference effects between lifting surfaces and intersections.

The tandem wing/twin boom design in figure 4.1b has promise of a lower structural weight. This is because the span-loading concept of spreading the aircraft weight along the wing minimizes bending moments on the wing that cause higher structural weights. This was dramatically demonstrated in the Rutan Voyager aircraft in which the very heavy fuel load was moved outboard on the wings in the two outer booms. The resulting structural weight was

TABLE 4.1.– SYSTEM-LEVEL ALTERNATIVES

- Configuration
  - All-wing
  - Cantilever monoplane
  - Biplane
  - Joined wing
  - Ultralight
- Operational Mode
  - Manned
  - Unmanned
- Launch
  - Conventional runway (with landing gear or trolley)
  - Carrier-aircraft drop
  - Rocket launch or boost
  - Balloon ascent
  - Towed flight

9.7% of the total aircraft weight compared with about 25% for conventional aircraft configurations. However, the aerodynamic drag of the Voyager proved to be about twice that of modern sailplane designs having the same wing shape (aspect ratio), and requires more power and fuel. A tradeoff study must be made to determine the optimum configuration for high-altitude flight.

Figure 4.1c illustrates a conventional monoplane design. For monoplanes, a large technical base helps establish confidence in the prediction of structural and aerodynamic efficiencies. For example, a very good data base exists in the design of modern sailplanes, which make use of modern composite carbon structures and low-drag aerodynamic shapes.

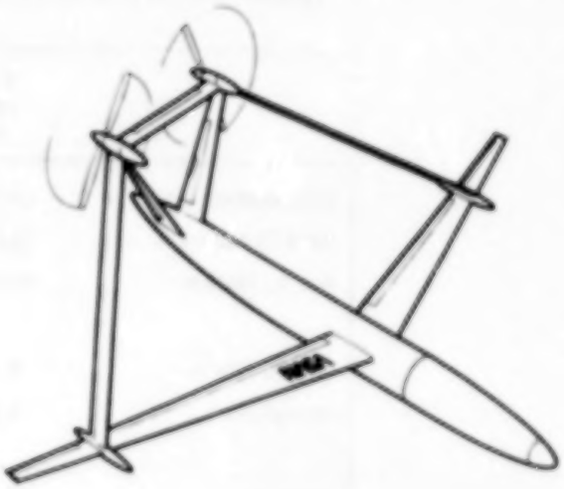

Figure 4.1a.– Joined wing design.

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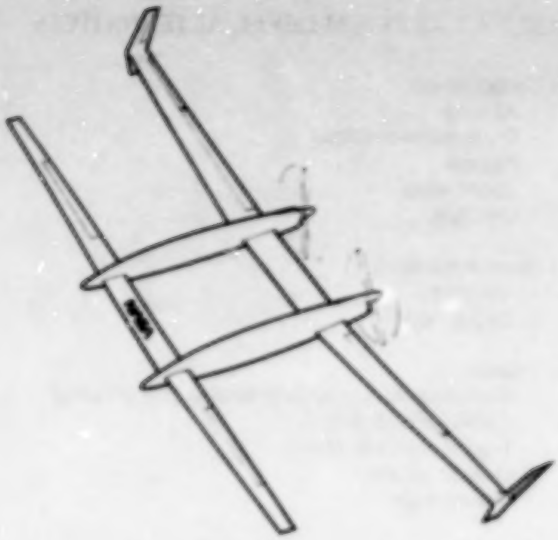


Figure 4.1b.– Tandem wing/twin boom design.

Figure 4.1c.– Conventional monoplane design.

The second system-level alternative in table 4.1 is manned versus unmanned design. The unmanned design can be optimized for higher performance by eliminating the weight (600 to 800 lb) of the pilot and the life support systems. Also, an unmanned aircraft may take much longer flights than manned aircraft because of pilot limits (8 hr). On the other hand, manned aircraft enhance the safety and flexibility in aircraft flight test and in flight operations from commercial airports and in commercial airspace.

The third system-level alternative in table 4.1 is the launch technique. The conventional runway takeoff is the simplest operationally and requires the minimum field equipment support. However, other launch methods may add performance to the vehicle by eliminating problems associated with lower altitude flights, for example, by eliminating climb fuel for the lower altitudes. Carrier-aircraft drop, rocket launch or boost, balloon ascent, and towed flight are alternatives to the conventional takeoff method. Serious consideration must be given, however, to the tradeoffs between increased vehicle altitude performance and increased operational complexity.

Structural Materials

Table 4.2 is a list of candidate aircraft structural materials and their physical properties. There is a good data base on the graphite/epoxy and Kevlar 49 composite materials and sufficient experience with these materials to design modern lightweight aircraft structures. However, new materials, such as Spectra 1000, show promise for use in developing weight-efficient aircraft structures.

TABLE 4.2.– PHYSICAL PROPERTIES OF STRUCTURAL MATERIALS

	Young's modulus, lb/in^2	Tensile strength, lb/in^2	Density, lb/in^2
5630 Stainless steel	30,000,000	110,000	0.278
2014-T6 Aluminum	10,500,000	61,000	0.101
6AL-4V Titanium	16,300,000	141,000	0.160
Graphite/Epoxy	8,000,000	70,000	0.053
Boron/Epoxy	9,580,000	85,000	0.068
Kevlar 49	18,000,000	525,000	0.052
Spectra 1000	25,000,000	435,000	0.035

Propulsion Systems

Table 4.3 is a list of propulsion system candidates for powering a very-high-altitude aircraft. Air-breathing turbine engines such as the turbojets used on the ER-2 lose power almost proportionally with atmospheric pressure. The ER-2 uses an oversized turbojet in order to have adequate power at 21 km (70,000 ft). A turbojet engine selected to operate at 30 km (100,000 ft) would have to be grossly oversized, requiring an engine almost 100 times larger than that needed at sea level.

TABLE 4.3.– PROPULSION SYSTEM CANDIDATES

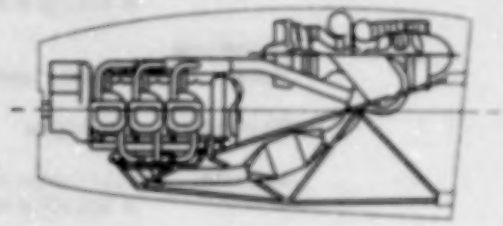
- Air-breathing turbine engine
- Air-breathing turbocharged reciprocating engine
- LOX-augmented air-breathing engine
- Monopropellant engine
- Fuel cell/electric motor
- Solar cells, microwave beam/electric motor
- Rocket
- Hybrid cycle engine

The air-breathing turbocharged reciprocating engine holds promise for operating at 30 km (100,000 ft). It has already been demonstrated to near 21 km (70,000 ft) altitudes on the Condor unmanned aircraft, with two stages of supercharging driving a large propeller system through a gear reduction box. Three stages of supercharging are required to operate at 30 km (100,000 ft) altitude. The weight and volume requirements for the supercharging equipment (turbochargers, intercoolers, heat exchangers, and ducting) increase dramatically from a two-stage system to a three-stage system for a given reciprocating engine. Figure 4.2 shows the size comparison in volume and weight for a 500-hp engine designed to operate at 21 km (70,000 ft) and at 30 km (100,000 ft).

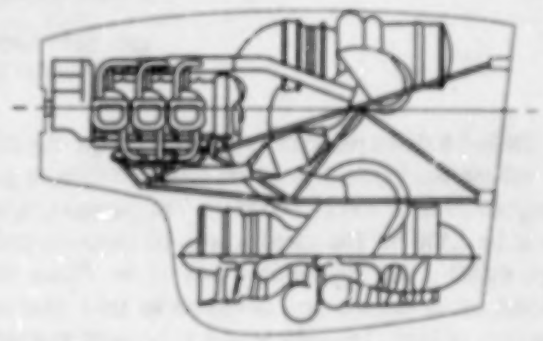
The other propulsion concepts in table 4.3 are specialized, their purposes ranging from missions having large payloads with short range or endurance to missions having small payloads with long endurance.

Very-High-Altitude Reference Aircraft Design

In order to establish some level of confidence in whether it is feasible to consider the development of a new aircraft to operate at altitudes of 30 km (100,000 ft) or higher, NASA Ames Research Center awarded a small study contract to Lockheed Aeronautical Systems (Reed, 1989). The study was given the acronym HAARP, for High-Altitude Atmospheric Research Platform. Lockheed teamed with Teledyne Continental Engines to establish maximum confidence in the propulsion technology. Lockheed was asked to consider only the state of the art in aerodynamics, structure, propulsion, and avionics in order to establish a conservative design approach. If such a vehicle could be designed and built, then any technology breakthroughs would only result in higher performance for the vehicle.



70,000 ft, 500 HP ENGINE
2-STAGE TURBOCHARGING



100,000 ft, 500 HP ENGINE
3-STAGE TURBOCHARGING

COMPONENT	WEIGHT, lb	
	70,000 ft ENGINE	100,000 ft ENGINE
DRY WEIGHT	445	445
TURBOCHARGER	578	735
COOLING SYSTEM	262	600
ACCESSORIES	196	226
TOTAL SYSTEM	1481	2006

Figure 4.2.– Weight and size comparison for a 500-hp engine designed to operate at 21 km (70,000 ft) and 30 km (100,000 ft).

TABLE 4.4.– HAARP PRELIMINARY REQUIREMENTS

Altitude:	100,000 ft with excursion to 120,000 ft
Payload:	2500 lb
Speed:	Subsonic
Range:	Total transit: 6000 n. mi. At 100,000 ft: 5000 n. mi.
Operational Mode:	Manned or unmanned
Propulsion:	Twin engine
Missions:	Polar (Antarctic) #1: Chile to South Pole to Chile, 5000 n. mi. at 100,000 ft with 2500 lb payload Polar (Antarctic) #2: Chile to South Pole to Chile, 5000 n. mi. at 70,000 ft with 4000 lb payload Midlatitude: NASA Ames to Chile, 5000 n. mi. at 100,000 ft with 2500 lb payload 120,000 ft: NASA Ames to Panama at 100,000 ft with excursion to 120,000 ft with 1000 lb payload

Table 4.4 shows preliminary HAARP design objectives. The vehicle was to cruise at 30 km (100,000 ft) with jump-up capability to 37 km (120,000 ft). The payload capacity was to be 2,500 lb. The speed was to be subsonic and the range 6,000 n.mi. The vehicle was to be flown either manned or unmanned and designed to take maximum advantage of both. The vehicle was to be twin-engined for reliability in returning to base in case of engine failure.

HAARP Missions

Four missions were devised for design purposes:

1. **Antarctic, 30 km:** Chile to South Pole to Chile, 5,000 n.mi. at 30 km (100,000 ft) with 2,500 lb payload.

2. **Antarctic, 4,000 lb:** Chile to South Pole to Chile, 5,000 n.mi. at 21 km (70,000 ft) with 4,000 lb payload.

3. **Midlatitude/Tropical, Two Hemispheres:** NASA Ames to Chile, 5,000 n.mi. at 30 km (100,000 ft) with 2,500 lb payload.

4. **Midlatitude/Tropical, Maximum Altitude:** NASA Ames to Panama, 3,250 n.mi. at 30 km (100,000 ft) with excursion to 37 km (120,000 ft) with 1,000 lb payload.

Figures 4.3-4.6 are artist's illustrations of the HAARP missions.

Table 4.5 lists operational considerations included in the HAARP aircraft design. A detailed listing of the operational considerations for a very-high-altitude aircraft that emerged from the workshop appears in chapter 5. In many cases these are elaborations of items already present in the HAARP reference design (table 4.5).

Figure 4.7 shows the sea level-to-altitude ratio of atmospheric pressure and density with 21 km (70,000 ft), 30 km (100,000 ft), and 37 km (120,000 ft) marked to represent the three mission altitudes specified for this design.

Design Challenges– Figure 4.8 illustrates the basic engineering challenges confronting the designer of this vehicle. The aerodynamic challenge is to maximize the aerodynamic parameter M^2C_L in order to operate at altitude with the highest wing loading (W_S) possible; this maximizes payload weight and aircraft performance. The aerodynamic graph in figure 4.8a shows that wing load limits are about 6 to 7 lb/ft^2 for 30 km (100,000 ft) altitude and 2 to 3 lb/ft^2 for 37 km (120,000 ft) altitude, if ER-2 aerodynamics are used. If modern airfoil technology is used, these wing loadings may be raised as high as 10 lb/ft^2 for 30 km (100,000 ft) altitude and 4 lb/ft^2 for 37 km (120,000 ft) altitude.

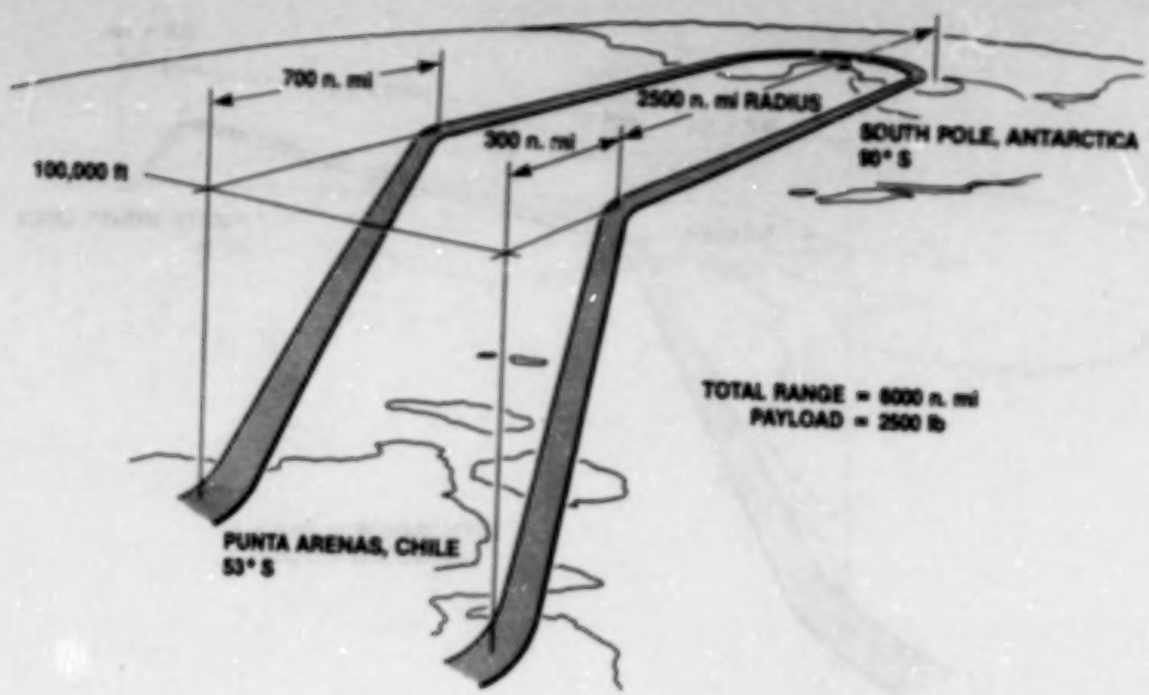


Figure 4.3.– Polar (Antarctic) Mission 1: Chile to South Pole to Chile, 5,000 n.mi. at 30 km (100,000 ft).

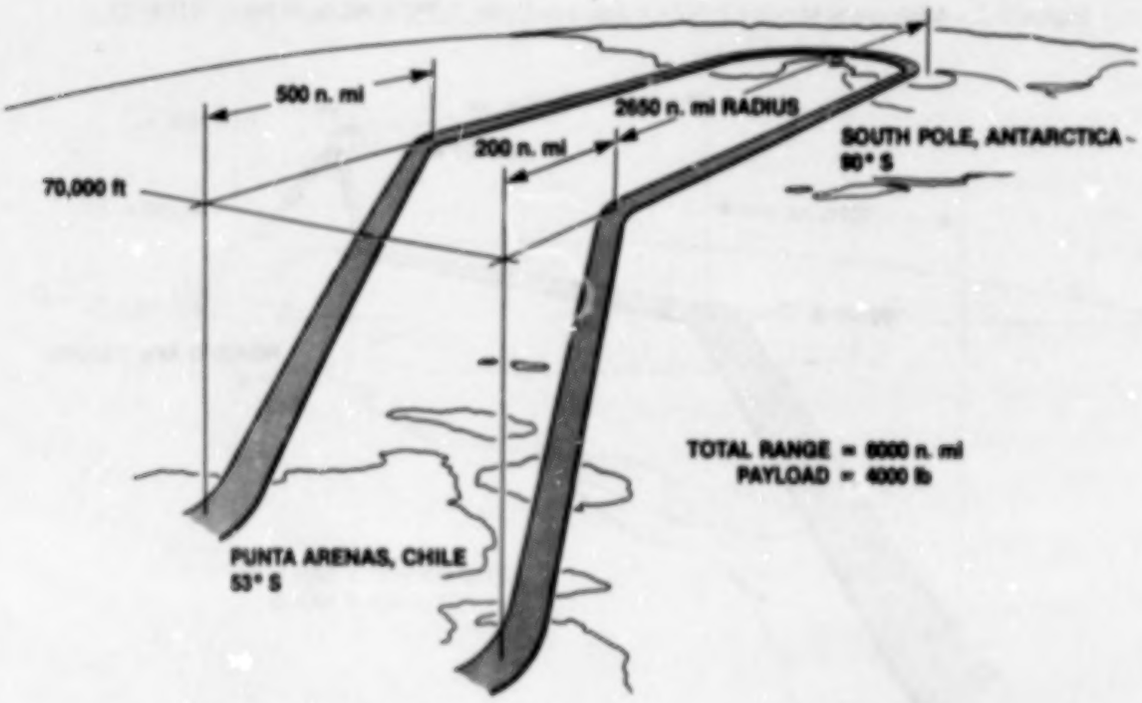


Figure 4.4.– Polar (Antarctic) Mission 2: Chile to South Pole to Chile, 5,000 n.mi. at 21 km (70,000 ft).

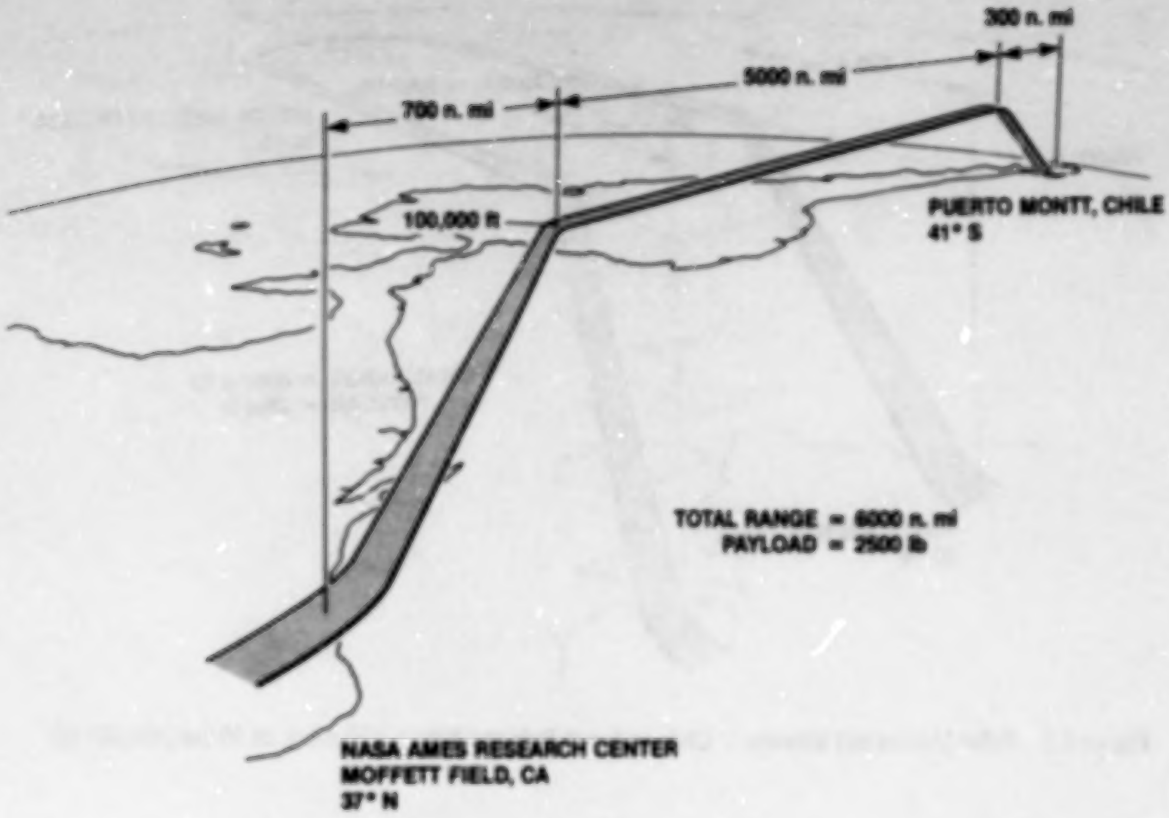


Figure 4.5.– Midlatitude Mission 3: NASA Ames to Chile, 5,000 n.mi. at 30 km (100,000 ft).

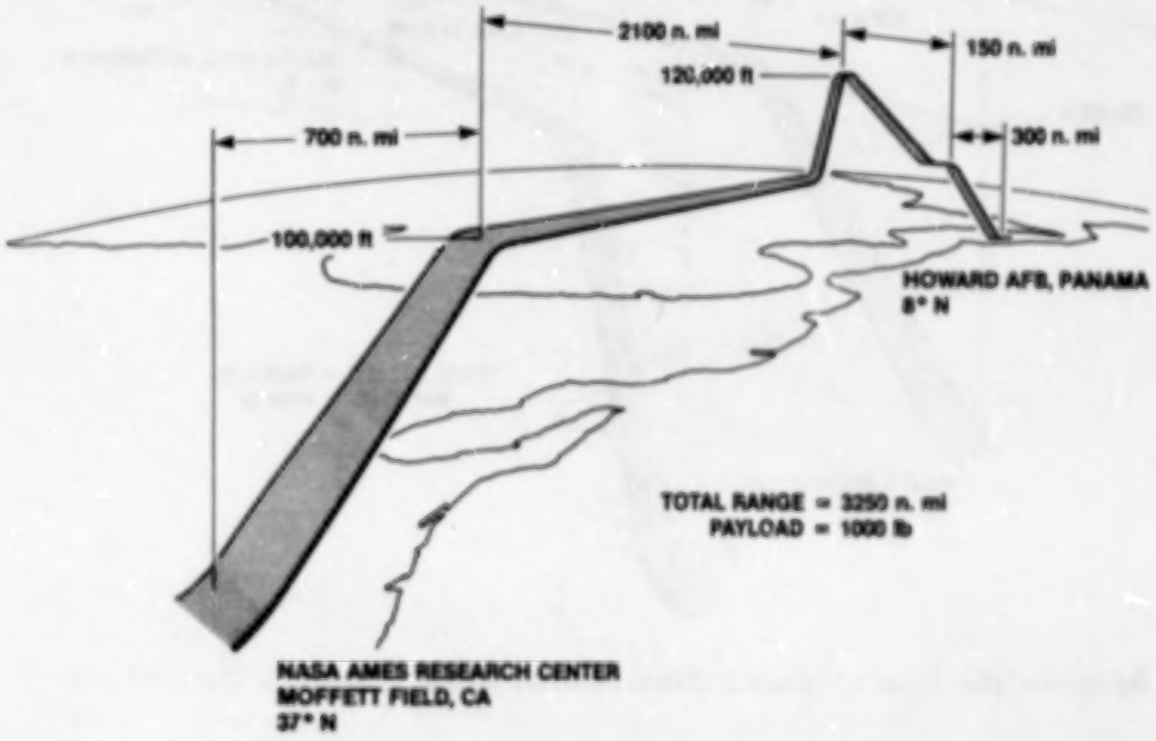


Figure 4.6.– 120,000-ft Mission 4: NASA Ames to Panama, 3,250 n.mi. at 30 km (100,000 ft) with excursion to 37 km (120,000 ft).

TABLE 4.5.– HAARP OPERATIONAL CONSIDERATIONS

- Design for man-in-cockpit since most missions will be manned
  - Aa features equal/better than ER-2
  - Redundant life support systems
  - Pilot friendly cockpit
- Operate from 75-foot-wide taxiway, 150-foot-wide runway
  - Wing span < 150 feet
  - Clear 4-foot-high obstacles 20 feet off runway/taxiway
- Crosswind capability > 15 knots
- Spoilers/lift dump devices for low wing load landing
- Operate in moderate to severe turbulence
- Adequate margin between stall and mach buffet
- Twin engine for mission flexibility/safety
- Hangar dimensions 110 feet x 70 feet

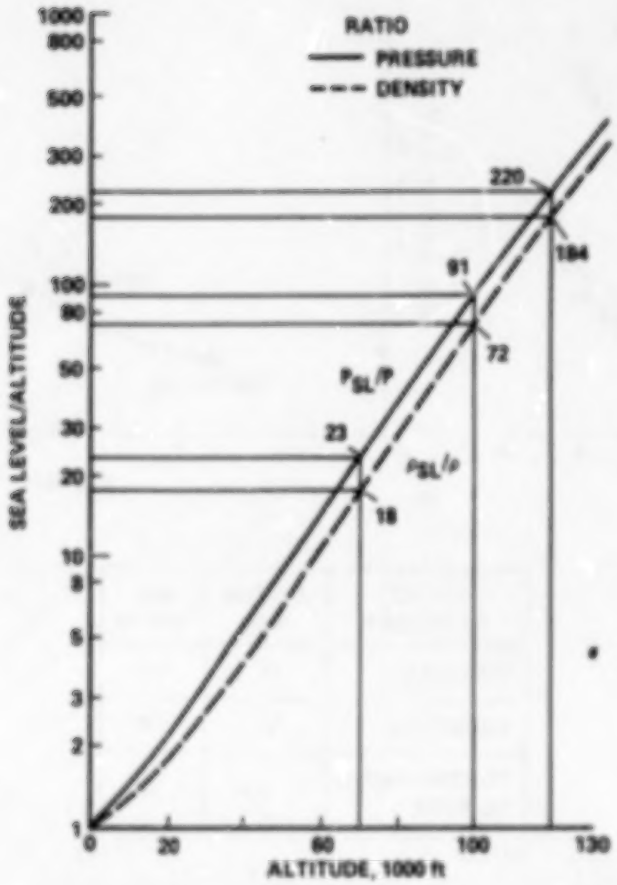


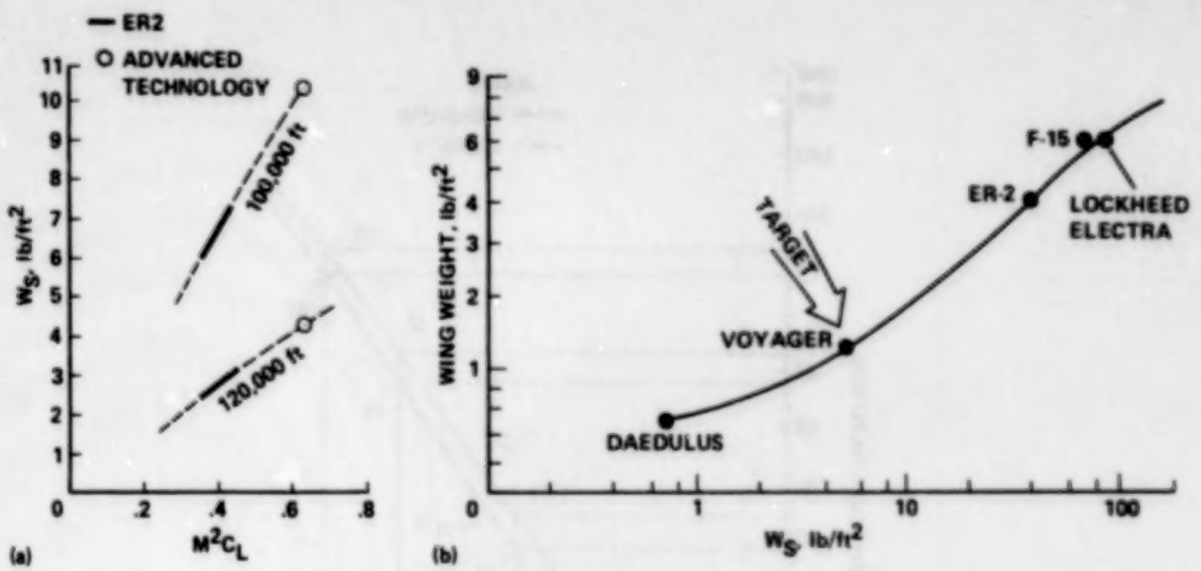
Figure 4.7.– Sea level-to-altitude atmospheric pressure and density ratios, with HAARP mission altitudes marked.

The structural challenge is to reduce the structural weight to meet the wing-loading requirements yet maintain robust capabilities to handle airloads, ground loads, and operational constraints in ground handling and in environmental conditions of temperature and moisture. Figure 4.8b shows that the wing weight must be near 1.2 lb/ft^2 of wing area to meet the mission altitude performance. The Rutan Voyager aircraft approximated this wing structural density. The ER-2 wing is shown on the graph for comparison at 4.0 lb/ft^2. Wing structural densities lower than 1.0 lb/ft^2, such as the man-powered Daedulus at about 0.4 lb/ft^2, are very frail and require special handling and weather restrictions.

The propulsion challenge is shown in figure 4.8c by comparing specific fuel consumptions and weights between turbojet, turboprop, and turbocharged internal combustion engines. Because both the turbojet and turboprop engines must be oversized drastically to obtain adequate thrust at 30 km (100,000 ft), the engine weights do not compete with the turbocharged internal combustion engine.

The propeller design challenge is illustrated by the basic propeller power equation: $H_p = C_p N^3 D^5 \rho$ where H_p is power transmitted by the propeller, C_p is the propeller power coefficient, N is revolutions per minute, D is propeller diameter, and ρ is atmospheric density. The atmospheric density drives the propeller design much as the atmospheric density drives the aircraft wing design. As can be seen from the equation, the propeller's power, H_p, is directly proportional to the atmospheric density. Because the atmospheric density at 30 km (100,000 ft) is approximately 1/70 that at sea level, a given propeller design can only transmit 1/70 the power at 30 km (100,000 ft) as at sea level.

This power may be increased by increasing C_p, N, or D. Changing the blade shape and increasing the number of blades can increase C_p, but going from two to four blades,



CONCEPT AT 100,000 ft	SYSTEM lb/hp	SFC lb/hp hr
TURBOJET	15	0.8
TURBOPROP	30	0.6
TURBOCHARGED I.C. RECIP	5.3	0.4

(c)

Figure 4.8.– HAARP design challenges. (a) Aerodynamic design goal shown by the symbol Θ for M = 0.7 and C_L = 1.3. (b) Structural requirement of 1.2 lb/ft^2 (indicated by target arrow in the plot) wing density to meet mission altitude goal of 37 km (120,000 ft). (c) Weight-to-power ratio and specific fuel consumption for several engine types.

for example, only increases the power transmitting capability by about three times at most, far short of the factor of 70 increase needed.

The value of N can be increased but is limited by the propeller tip Mach number, which is about 1.0, and it depends slightly on the propeller shape. This leaves the most powerful parameter, the propeller diameter to the fifth power. The resulting propeller requirement is calculated to be a 24-ft diameter, two-bladed propeller for 220 hp transmitted at 30 km (100,000 ft).

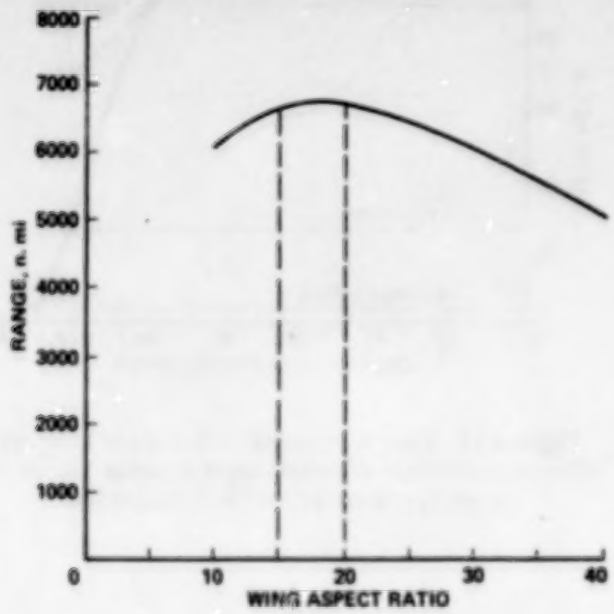


Figure 4.9.– Range versus wing aspect ratio for a cruise altitude of 30 km (100,000 ft) and a takeoff weight of 15,000 lb.

Figure 4.9 is a plot of aircraft range at 30 km (100,000 ft) altitude versus wing aspect ratio. This plot is the result of a computer study of tradeoffs between aircraft having high aspect ratio (sailplane) wings with low drag (low power requirement) and aircraft having low aspect ratio wings (less bending moment, lower structural weight) with a greater fuel weight allotment. An aspect ratio between 15 and 20 gives the optimum range, near 6,500 n.mi. For cruise missions less than 21 km (70,000 ft) where weight is not as critical, higher aspect ratios are closer to optimum, e.g., the Condor configuration with an aspect ratio of 36. A wing with an aspect ratio of 15 was chosen, to limit the wing span for runway and hangar requirements, as well as to provide the best range at 30 km (100,000 ft).

Figure 4.10 shows the effect of payload weight on aircraft takeoff weight and wing span. An aircraft designed for a 2,500-lb payload is marked on the graph for reference.

To improve confidence in the feasibility of HAARP, the study included exploratory analyses of the following subjects:

Payload locations
Weight and balance
Aircraft weight fractions
Fuselage instrument location
Engine pod location
Availability of aircraft-qualified engines
Turbocharger equipment
Wingtip-pod instrument layout
Operation at 120,000 ft
Takeoff and landing operational modes
Ground service features
Airfoil design criteria

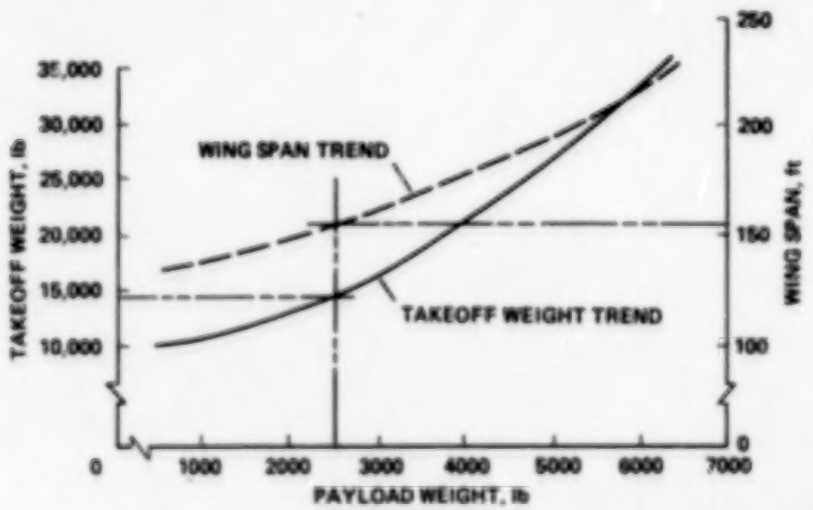


Figure 4.10.– Effect of payload weight on takeoff weight and wingspan. Total range is 6,000 n.mi.; range at 30 km (100,000 ft) is 5,000 n.mi.

Ground service features
Airfoil design criteria
Candidate airfoil section
Candidate propeller section
Estimated cooling requirements
Thermal control techniques
Ram air heat exchanger
Structural design criteria
Wing planform structure
Inboard wing structure
Fuselage structure
Flight control system,
Reaction control system.

HAARP Program Results

Figure 4.11 summarizes the current technical confidence in achieving subsonic cruise flight for various altitudes up to 40 km (130,000 ft). An altitude of 21 km (70,000 ft), where the U-2 and ER-2 currently can operate, has 100% confidence. The study conducted by Lockheed for HAARP gives a very high confidence level that a vehicle of this type can be designed and built using current technology. The vehicle will improve in performance if advanced technologies are developed and applied in the design of the HAARP vehicle. A 90% confidence is thus shown on the chart for a 30 km (100,000 ft) design. On the other hand, developing a vehicle to *cruise* in level flight at 37 km (120,000 ft) is extremely difficult and demands more than off-the-shelf technology. A 25% confidence level is thus shown on the chart for developing cruise flight at 37 km (120,000 ft). On the positive side, a jump-up or zoom to 37 km (120,000 ft) from a 30 km (100,000 ft) cruise is more easily achievable and is given a 65% confidence level as a special case. A 40-km (130,000-ft) cruise design is very nearly out of the question with today's technology and is given about a 5% confidence value.

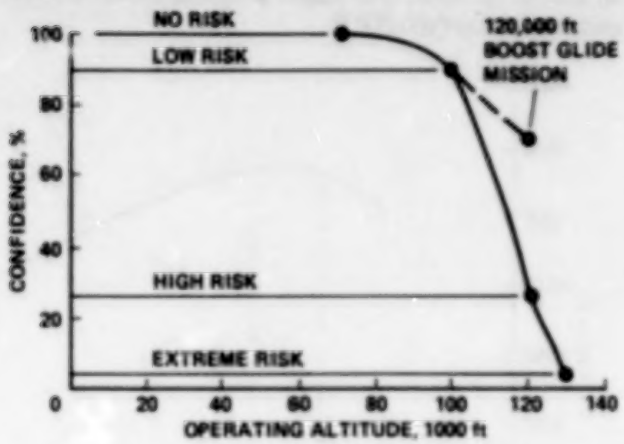


Figure 4.11.– Current technical confidence in achieving subsonic cruise flight at various target altitudes. The no-risk point represents current ER-2 technology.

5. REQUIRED VERY-HIGH-ALTITUDE AIRCRAFT CHARACTERISTICS

The extensive and varied science requirements discussed in the previous sections cannot be satisfied by a single aircraft design. Most of the requirements can be met by a higher-flying complement to the ER-2—a multi-investigator, mission-oriented, facility platform. The additional requirements would be too expensive to fulfill with a more complex design of this aircraft. They can, however, be satisfied by specialized designs that address the requirements of certain upper atmospheric science questions.

Multi-Investigator, Mission-Oriented, Facility Platform

The goal of this platform is to carry large, multi-instrument payloads to any spot on the globe at 30 km (100,000 ft) cruise altitude. This platform could provide further elucidation of the polar ozone depletion phenomenon, equatorial and tropical chemistry and dynamics, and the composition and evolution of volcanic plumes in the upper atmosphere. The rough specifications for this aircraft are shown in table 5.1.

Operational Considerations– A multiple engine design is preferred for the very-high-altitude aircraft over a single engine design, and the aircraft must be capable of flight with one engine inoperative. If fly-by-wire flight controls are used, redundant systems are required. The flight and engine envelopes at operational altitudes must be no smaller than those of the ER-2 (approximately 15 knots and 20% of engine thrust).

The aircraft must operate on narrow taxiways (the desired goal is 60-ft-wide taxiways, although the requirement is 75 ft wide) and on 150-ft by 6,000-ft runways. Wings must avoid common obstacles such as lighting and signs up to 4 ft high that are as close as 20 ft to taxiways and runways, and the aircraft must fit into a hangar 98 ft wide.

TABLE 5.1.– SCIENCE REQUIREMENTS, VERY-HIGH-ALTITUDE AIRCRAFT

Altitude:	100,000 ft with desired excursion to 120,000 ft
Payload Weight:	3000 lb
Payload Location:	In situ instruments: Forward-looking access to the unperturbed free air stream
	Remote sensors: Access to upward, downward, and horizontal views
Speed:	Subsonic; M = 0.7, variable down to M = 0.4 to test experimental inlet losses
Range:	6000 n. mi., including vertical profile from cruise to 45,000 ft to cruise
Operational Mode:	Unmanned for long ranges, polar night flights, unrestricted flights over oceans, manned for special-purpose flights and populated airspaces
Operational Capabilities:	Over oceans; in dark; airfield/crosswind restrictions less than or equal to ER-2
Vibration:	Equal or less than the ER-2
Aircraft Wiring:	Must accomodate rapid instrument swapping and communication between instruments and master control computer
Telemetry:	Tracking and Data Relay Satellite System for commands and data
Number Required:	Two operational aircraft

The ability to take off and land in 15 knots of crosswind, 200-ft cloud ceilings, and 0.5-mile visibility is necessary, as is the ability to fly through moderate turbulence. (The ER-2 structural strength provides a reasonable design of minimum load capability.) To cope with gusty winds during landings, a lift dumping system is required and an antiskid braking system is desired. Also, aircraft engine(s) and their associated fuel, fluids, and lubricants must be capable of coping with outside air temperatures as low as 100° C.

Toxic fuels are strongly discouraged for this aircraft as they will present difficulties for flight operations and maintenance; shipping and storage safety, the safety of personnel near the aircraft, and nervous host governments are problems that would have to be solved.

Redundant attitude and navigational systems are required. As potential operating areas have no ground-based navigational aids, an inertial navigation system with Global Positioning System update is a likely navigation system candidate. Avionics for air traffic control transponding and altitude reporting are also required, as well as an Emergency Locater Transmitter operating on 121.5 and 406 MHz.

Cockpit Considerations– Although the very-high-altitude aircraft will often fly unmanned, manned flight will be required on some occasions. For example, some potential flightpaths are near sensitive political borders; this requires pilot monitoring of the flightpath. Some host governments may not allow unmanned aircraft to fly through their airspace. Science data collection sometimes requires human observation of in-flight conditions to optimize the data, and some science payloads may require pilot interaction. So the cockpit must be designed for occupation by a pilot.

The cockpit layout should be similar to that of the ER-2 to aid pilot familiarity and ease the transition between the ER-2 and the new research aircraft. Commonality between the avionics of the ER-2 and the new aircraft would also minimize logistic support and maintenance costs.

The cockpit must be sized for the same full pressure suit used in the ER-2, and must provide oxygen and suit-cooling air sources as well. It must provide adequate access for life support technicians to integrate the pilot into the cockpit. Compatibility with the current crew access stand is desired.

All cockpit controls, displays, instruments, and circuit breakers must be accessible and within visual range of a pilot wearing a full pressure suit and strapped in the cockpit. If fly-by-wire flight controls are used, a centrally mounted yoke or stick is preferred over a side controller. A means to visually determine the aircraft's position accurately, such as the optical viewsight in the ER-2 or an electro-optical device, is required, and the pilot's forward, side, and downward visibility from the cockpit must be no less than that of the ER-2.

Life support systems (oxygen, suit faceplate heat, suit-cooling air, ejection seat, and air conditioning) and the canopy/windshield defog system should be similar to ER-2 systems, with at least as much redundancy and inherent safety features as found in the ER-2. The cockpit pressurization must not exceed 29,000-ft cabin altitude at its maximum altitude for manned flight. Cockpit pressurization must have priority over payload compartments. A means to shut off pressurization flow to the payload areas is required if the design allows a decrease in cockpit pressure as a result of a payload area leak.

A storage area for pilot foods and fluids is required, although a food heater is not needed. A system for the pilot to pass urine from the suit to a cockpit reservoir is required.

Additional Considerations– Other useful features are the abilities to fly at constant potential temperature either on automatic pilotless control or on autopilot, and to record all control signals generated by pilot, autopilot, or computer, so they can be used to improve the interpretation of waves through which the aircraft passes.

It is suggested that all experiments accepted for deployment on the very-high-altitude aircraft be able to reduce their data in near real time on board the aircraft. This would cut down on the data stream required to decide how the aircraft flight track may be changed to detect phenomena of interest. Those decisions could, of course, be made by the onboard master control computer. One possible operating mode would be to find the maximum in an atmospheric constituent or state variable and then make a vertical profile through the space of interest.

It is particularly important that this aircraft be capable of very high resolution meteorological measurements. Accurate temperature, pressure, and wind information are necessary for the interpretation of scientific results.

The specifications given in this chapter clearly cannot answer all the science-capability questions that will arise during the design and development of the subject aircraft. Thus it is extremely important that a science review committee be established, to provide continuing oversight and periodic reviews, and to decide on necessary compromises (e.g., between ceiling altitude, range, and payload capacity) that arise during the design and construction phase. This committee should also provide counsel on instrument modification, selection, and development, so that

instruments and aircraft are ready for science missions at the same time.

Special-Purpose Aircraft

The platform requirements implied by the science in this report are in many ways a call for a better high-altitude balloon. For example, a fairly cheap, easily deployed, short duration platform to carry 100 lb or so to medium altitudes ~24 km (80,000 ft) would allow measurements in the polar vortices in midwinter, to determine the initial conditions that set up the polar ozone phenomena. Currently this mission cannot be done by either balloon or aircraft; the target region is too dark, cold, and distant for the ER-2, and the cold is too high for balloons because of the inability to recover the payload.

To address problems associated with photochemical equilibrium one needs to get above 30 km (100,000 ft), to perhaps 40 km (130,000 ft). These problems often require floating at one altitude during sunrise or sunset. Balloons have limited launch sites, not necessarily located near the problem of interest, and they cannot stay at one location ("station keep") while watching the development of the atmosphere with time. (During the important times of the year, balloons float out of the allowed air space before the experiment can be completed.)

Studies indicate that these questions can be addressed with aircraft platforms. The development of platforms to meet the requirements that cannot be met by the facility aircraft should be encouraged. In addition, this capability can be particularly valuable for evaluating new instrument concepts, for providing opportunities for student involvement in upper atmospheric research, and for giving complementary measurements to large spacecraft and aircraft missions.

6. URGENCY: AIRCRAFT AND INSTRUMENTS

As discussed in chapter 2, a number of important problems in atmospheric science can best be addressed by an aircraft capable of flight at or above 30 km (100,000 ft). Many of these questions are of considerable significance to society in general and to the United States in particular. For example, regulation of CFCs, including the replacement of current forms with substitutes that are less harmful to the ozone layer, affect not only a multibillion-dollar-per-year industry, but also nearly the entire human population, through refrigeration, insulation, and other widespread uses. A number of developed-world versus third-world conflicts have already occurred over proposed international regulations.

In a joint report to President Bush, the National Academies of Science and of Engineering, and the Institute of Medicine, stated:

> We are already irrevocably committed to major global change in the years ahead. The elevated concentration of greenhouse gases produced to date by human activities will persist for many centuries and will slowly change the climate of the Earth, regardless of our actions. The chlorofluorocarbons (CFCs) that are depleting the ozone shield have lifetimes on the order of a century. (National Academy of Sciences, 1988)

President Bush is anxious that the United States play a major role in any international effort to protect the global environment. International agreements are being considered. For example, in March 1989, Prime Minister Margaret Thatcher hosted an international conference to alter the conditions of the Montreal Protocol to a complete phase out of CFCs by the year 2000. Several European countries and the United States agreed, while some other countries did not.

Future observations of the ozone layer and a better understanding of its chemistry will play a critical role throughout the rest of this century in developing a wise regulatory policy. An ongoing investigation of the chemistry of the stratosphere is required, to be certain that proposed substitutes do not also destroy ozone. Likewise, the development of high-altitude supersonic aircraft that do not destroy ozone is under consideration; such development would impact the major export of the United States, aircraft. This issue, which is just now being studied again, will also continue through the rest of the century and beyond.

Frank Press, Robert White and Samuel Thies (presidents of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine, respectively) stated:

> Embedded in the diverse manifestations of this problem—global warming, ozone depletion, tropical deforestation, and acid deposition—are enormous challenges to science and engineering, to your Administration, and to the world community of nations. In many instances, data and analyses are incomplete and long-term effects remain indeterminate; in addition, there are costs to the economy embedded in any decisions made to address the problem. Yet, even with a continuing background of uncertainty, it is important to recognize that human activities are indeed changing the global environment. Prudent courses of action need to be initiated now to try to understand and predict these changes, and to move toward suitable policy responses. (National Academy of Sciences, 1988)

Because of the great economic, environmental and social importance of issues such as these, and because of the lack of ability to address some aspects of these issues with current techniques, we believe that the aircraft discussed here should be built as rapidly as engineering and construction practicalities will allow.

Research in the upper atmosphere will be largely conducted by the UARS during the early 1990s. The satellite will be launched in 1991, and one of its most important instruments (CLAES) will run out of cryogen in mid-1993. The aircraft discussed here would make an important contribution to the validation and extension of the data from this satellite, if the aircraft could be operational while some of the satellite instruments are still operating.

Similarly, the NDSC, an array of ground-based upper atmosphere remote sensing instruments, will become operational near 1995. The very-high-altitude aircraft proposed here could perform an important role in cross calibrating NDSC stations and satellites via correlative measurements made above the stations in conjunction with satellite overpasses.

In order to fully utilize the very-high-altitude aircraft it will be necessary to modify the ER-2 instruments or build new instruments for the lower operating pressures of the new aircraft. It is especially important that instruments measuring ozone, reactive nitrogen, reactive chlorine, dynamical tracers such as N_2O, and aerosol sizes and properties be available as soon as the aircraft is ready so that observations can be initiated promptly. The development of spectral radiometers to study the radiation profiles that determine the greenhouse effect and stratospheric diabatic motions is also

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very important. For these reasons we recommend that instrument development and modification be done in parallel with the development of the aircraft.

The science review committee that monitors design and development of the aircraft should also recommend and monitor the development of instruments that will best address the science questions to be studied when the aircraft becomes available for science research.

APPENDIX A: AIRCRAFT SPEED: SUBSONIC VERSUS SUPERSONIC

An important issue in stratospheric research is the effect of sampling at high Mach numbers on the accuracy of data. Calculations show that for direct sampling (pitot tube facing forward), even the O_2-to-N_2 ratio is affected at a Mach number of 3.5. Thus if we are to use aircraft at large Mach numbers we must find a way to avoid passing the particles and gases to be sampled through the shock front , and at the same time avoid heating them from adiabatic compression (fig. A1). The shock front can be avoided by using a cooled, flat plate that has a small (<5°) negative inclination to the free air stream, and heating can, in large measure, be avoided if the temperature is held at the free air stream temperature. One disadvantage of this method is that one loses the normal pressure increase that has been used in the past to drive the gases and particles through the detectors; hence, one must use a pump. The other problem is that, in this method, the sampling is done from inside the boundary layer, so the gases have a higher probability of having contacted a wall, suffering either wall-catalyzed reaction or contamination by gases from the wall. These problems all seem soluble, given enough time and money to find the right wall material, but contamination of the wall material on the ground and during ascent, as well as outgassing from the wall, may well complicate the situation.

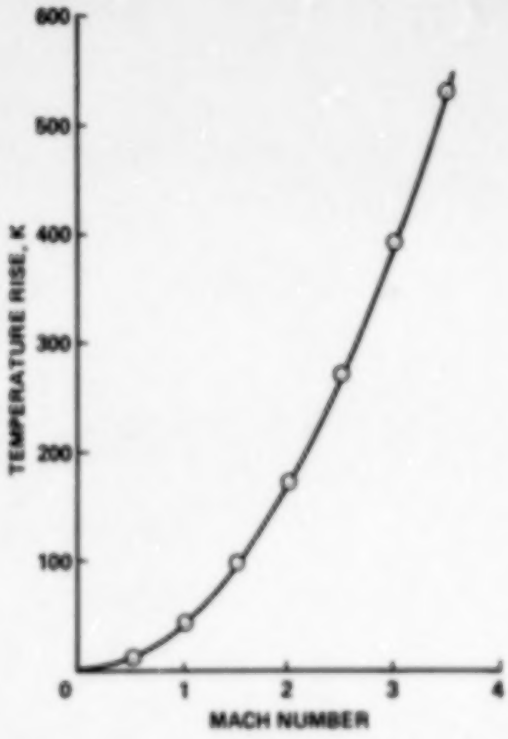

Figure A1.– Temperature rise versus Mach number for a forward-facing pitot tube at an ambient air temperature of -50°C.

The situation for particles is much more complicated since the particle's momentum in the sampling process is significant. In order to sample from the flat plate, the air stream must be turned into the plate. That is possible for gases, but larger particles may not turn enough for sampling. (At a Mach number of 1, one might be unable to sample particles larger than about 50 μm.) Large particles could be sampled with a normal forward-looking collector, but this would result in high evaporation rates, as well as complications in the data analysis caused by the lack of an isokinetic sampling system. It would be impossible to use a wire impactor or filter sampler at high Mach number because all but the very largest particles would evaporate before collection.

It is unclear whether any complications arise in remote sensing. The emissions from the shock front may well affect infrared emission measurements. We have not been able to obtain any estimates of how large this effect would be on the infrared radiometers; these estimates would have to be made before one could accept a platform of Mach number > 1.

Another difficulty with the supersonic approach is the much higher construction and operating costs. For example, the additional cost of in-flight refueling of the aircraft would be incurred. This is only one of the many operational difficulties that are associated with a supersonic aircraft. Therefore, since it is apparent from the body of this document that subsonic aircraft can meet all of the science requirements, subsonic aircraft should be used.

APPENDIX B: ATMOSPHERIC REMOTE SENSING FROM A VERY-HIGH-ALTITUDE AIRCRAFT

Remote sensing measurements can make unique contributions to stratospheric research from a very-high-altitude aircraft. Critical issues in the study of polar stratospheric chemistry and dynamics, photochemistry in the tropics and midlatitudes, transport of chemical species by the large-scale atmospheric circulations, and the Earth's radiation balance can be addressed by a combination of remote and in situ instrumentation operating from a high-altitude (30 km/100,000 ft) aircraft on long-range (6,000 n.mi.) flights. This appendix discusses the capabilities of remote sensing instrumentation and the contribution that remote sensing can make to the study of the important atmospheric science topics identified above.

Remote sensing instruments use either active or passive techniques in making measurements of gases, aerosols, or radiation some distance from the aircraft. Active remote sensing techniques use a light source, which could be a laser in some applications, that is part of the instrument. Hence, measurements can be independent of solar illumination (apart from the interference of scattered sunlight). Most passive measurements rely on either viewing the sun directly or detecting scattered sunlight. However, one class of pessive instruments uses the infrared emission from gases in the atmosphere for their measurements. In general, active remote sensing techniques can provide high spatial resolution profiles of a few gases and aerosols/clouds over ranges up to 20 km (65,000 ft) above or below the aircraft, whereas passive techniques can provide column and low-vertical resolution measurements of many gases above and, in some cases, below the aircraft. Active remote sensing measurements of ozone, water vapor, and aerosols/clouds, as well as passive remote sensing measurements of many trace stratospheric gases and radiation budgets, can be made from a very-high-altitude aircraft. Each of the possible remote sensing techniques that could be applied to the stratospheric missions identified in chapter 2 are discussed below.

Atmospheric cross-sections of ozone can be obtained above and below a very-high-altitude aircraft using a differential absorption lidar (DIAL) technique. High vertical resolution DIAL measurements of ozone can provide unique information in ozone depletion studies and in the investigation of atmospheric dynamics using ozone as a tracer of motions. Real-time ozone distribution information below the aircraft can provide information for determining in situ sampling strategies with the same or another aircraft. An airborne lidar can also be used to determine the location and type of polar stratospheric clouds and the distribution of background stratospheric aerosols. The use of multiple lidar wavelengths and depolarization measurements can help characterize the aerosols and polar stratospheric clouds, and the lidar can be used for real-time decisions about aircraft sampling of these layers. In addition to ozone and aerosols/clouds, an advanced DIAL system could be used for obtaining profiles of H_2O in the lower stratosphere. The information on H_2O is important for determining the degree and extent of dehydration in the polar vortex, and for studying atmospheric dynamics using H_2O as a tracer.

Passive measurements of solar absorption in the infrared and ultraviolet can be used to obtain the column content of gases that are important to understanding the chemistry associated with ozone depletion in the polar regions and the processes that determine the natural distribution of gases in the middle to upper stratosphere. The solar occultation measurements can be made any time the sun is up; the infrared emission measurements could be made in daylight or at night to provide low spatial resolution gas measurements for examining the diurnal variation of key species. Some of the gases that can be measured with passive instruments include HO_2, HOCl, COF_2, pernitric acid, HF, HCl, HNO_3, $ClONO_2$, NO_2, BrO, OClO, and O_3.

Remote measurements on the DC-8 were a key means of revealing the complex processes at work in Antarctic and Arctic ozone chemistry, but important questions remain, in part because the vertical resolution of the passive measurements was coarse or lacking altogether. A very-high-altitude aircraft would provide a considerable improvement in vertical resolution, either by flying vertical profiles through the altitude region of interest, or by inverting angular-scan measurements made from the aircraft's maximum or cruise altitude. Vertical profiles inverted from downward angular scans provide inherently finer vertical resolution than those from upward scans, because of the combination of the spherical geometry with the downward increase in atmospheric density.

Infrared spectral radiometers can be used to obtain the nadir and zenith radiation flux associated with thin aerosol/cloud layers that will be within the altitude range of the very-high-altitude aircraft. The impact of the heating/cooling of the atmosphere from the presence of these layers can then be determined. The ER-2 ceiling is below the altitude of many polar stratospheric clouds, especially in the Arctic; hence, measurements of aerosol/cloud radiative effects would benefit greatly from higher altitudes, as well as from the capability to sample in the polar night, over water far from land, and at great ranges from the aircraft base.

Gases with very low concentrations and with small spatial scale variations in the lower stratosphere can be studied

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with a long-path absorption technique in the vicinity of the aircraft. Using two aircraft or one aircraft with a tether, an absorption path length of 3,000 ft or more could be obtained between a light source and a detector. A retroreflector on the second aircraft or at the end of the tether may be used to collocate the source and detector in one instrument. This technique may permit the measurement of important stratospheric radicals, intermediates, and reservoir species that currently cannot be measured in situ. The gases that could be measured with this technique include OH, HF, HCl, N_2O_5, H_2O_2, and $ClOF_2$. Understanding the distribution of these gases would contribute greatly to the understanding of ozone depletion chemistry and stratospheric photochemistry in general.

It should be stressed that while remote sensing measurements can provide unique information about the stratosphere, the combination of these measurements with a comprehensive set of in situ measurements is necessary for addressing the stratospheric science missions discussed in chapter 2. This may require two very-high-altitude aircraft with different instrument complements. In addition, to take advantage of the information derived from the remote sensing instruments for determining in situ sampling strategies, there must be onboard data processing for the remotely sensed data and telemetry of this data to the ground for real-time mission decisions.

APPENDIX C: ACRONYMS AND DEFINITIONS

AAOE	Airborne Antarctic Ozone Experiment
AASE	Airborne Arctic Stratospheric Expedition
CFC	Chlorofluorocarbons
CLAES	Cryogenic Limb Array Etalon Spectrometer, on UARS
Condor	High altitude autonomous aircraft using twin engine propeller configuration
DC-8	Four-engine jet research aircraft deployed from NASA Ames Research Center
DIAL	Differential absorption lidar
Eos	Earth observing system
ER-2	Advanced version of U-2 type aircraft deployed from NASA Ames Research Center
Fabry-Perot	Interferometric infrared spectrometer
FTIR	Fourier Transform Infrared Spectrometer
HAARP	High-Altitude Atmospheric Research Platform
HALOE	Halogen Occultation Experiment
ISAMS	Improved Stratosphere Mesosphere Sounder
NDSC	Network for the Detection of Stratospheric Change
Nimbus-7	Satellite carrying sensors for study of atmospheric and oceanic processes
NOZE	National Ozone Expedition
SAGE	Stratospheric Aerosol and Gas Experiment
SAM	Stratospheric Aerosol Measurement, on Nimbus-7
SBUV	Solar Backscatter Ultraviolet, ozone profiler on Nimbus-7
TOMS	Total Ozone Mapping Spectrometer, on Nimbus-7
UARS	Upper Atmosphere Research Satellite

APPENDIX D: REFERENCES

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16. Abstract

A workshop entitled Requirements for a Very-High-Altitude Aircraft for Atmospheric Research was held at Truckee, California, on July 15-16, 1989, sponsored by NASA Ames Research Center. The workshop addressed two main topics: 1) Is the development of a new, very-high-altitude aircraft justified by current critical, unanswered questions in stratospheric research, and 2) What are the requirements of a new aircraft designed to address these scientific questions? This report examines four paradigmatic missions of the new aircraft and discusses the impact of subsonic versus supersonic flight on gas and aerosol sampling. The report summarizes and elaborates on the workshop consensus that an aircraft of increased capability over the current ER-2 high-altitude platform is required within the next 5 years to acquire data on critical, unanswered questions in stratospheric research. The new aircraft would have to provide a flight mission envelope of 100,000 ft cruise altitude with a total mission range of 6,000 n.mi. An aircraft jump-up capability for short cruise periods at 120,000 ft is highly desirable.

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